Future Directions in CGC Studies at RHIC

L.C. Bland, BNL

RBRC Workshop on *Saturation*…

12 May 2010

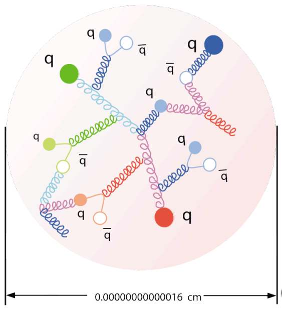
*My personal viewpoint is that pursuit of **Drell Yan production in the forward direction** is the best possible future for spin and low-x physics at RHIC, and will provide the best possible complement to eRHIC.*

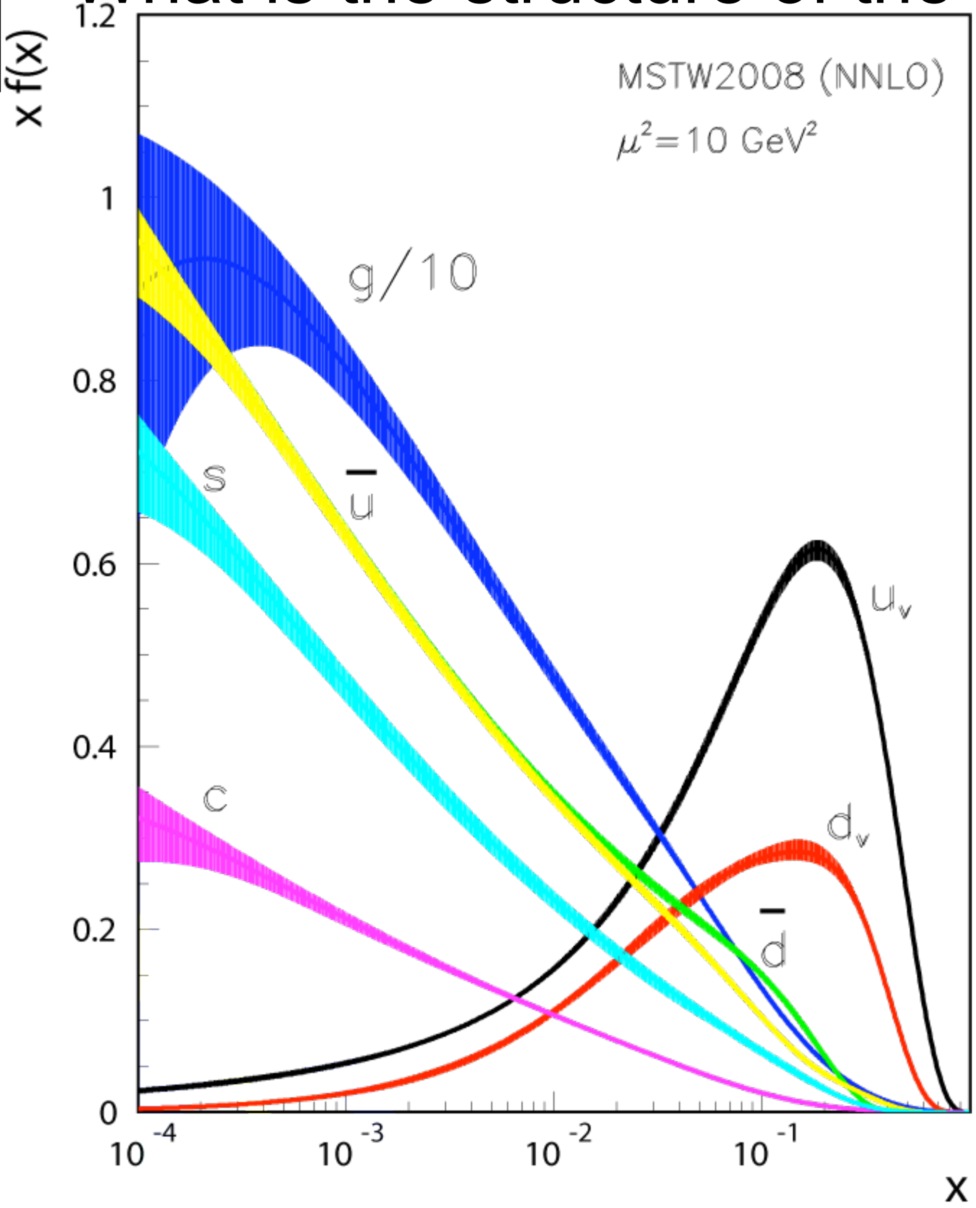
Disclaimer

To achieve understanding of strongly interacting systems is complicated. Talking about the future is even more complicated. Hopefully this satisfies the request for a talk on **Future Directions in CGC Studies at RHIC**. To talk about the future, it is best to understand the past and the present. Your patience with some ramblings about spin things would be appreciated, since there appears to be overlap of where interesting spin phenomena appear and where interesting low-x phenomena appear and the very strong possibility that colored baggage plays an important role for both phenomena. **Future Directions at RHIC should keep eRHIC in mind.** If the goal is understanding, then trying to identify universal phenomena common between hadro-production and electro-production looks to be the most important thing we can try to do.

Goals I

What is the structure of the proton?

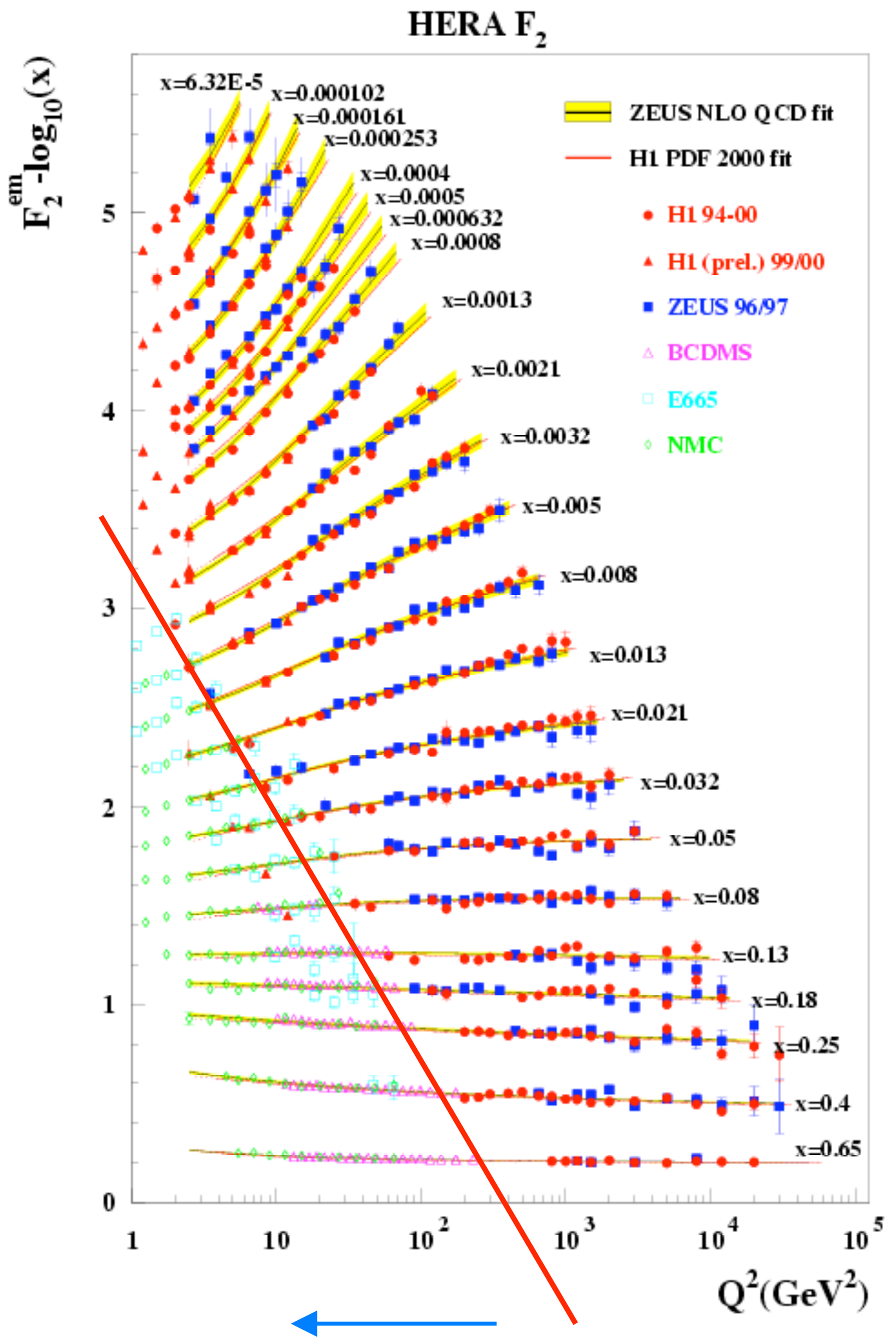




Proton structure is understood via *parton distribution functions* f(x). These functions are global fits to world data and give the probability to find a parton (quark, gluon or antiquark) carrying a fraction x of the proton's momentum.

…and then there is spin!

World Data for (unpolarized) DIS



Fixed Target Experiments

Combination of fixed-target experiments and results from the HERA collider (DESY) provides a precise determination of the x and Q^2 dependence of the F_2 structure function and is the primary data for global fits to parton distribution functions.

Summary plot from arXiv:hep-ex/0507024, and references therein.

Rapid rise of the gluon density at low-x evident from $\partial F_2(x)/\partial \ln Q^2$ at fixed x (Prytz relation)

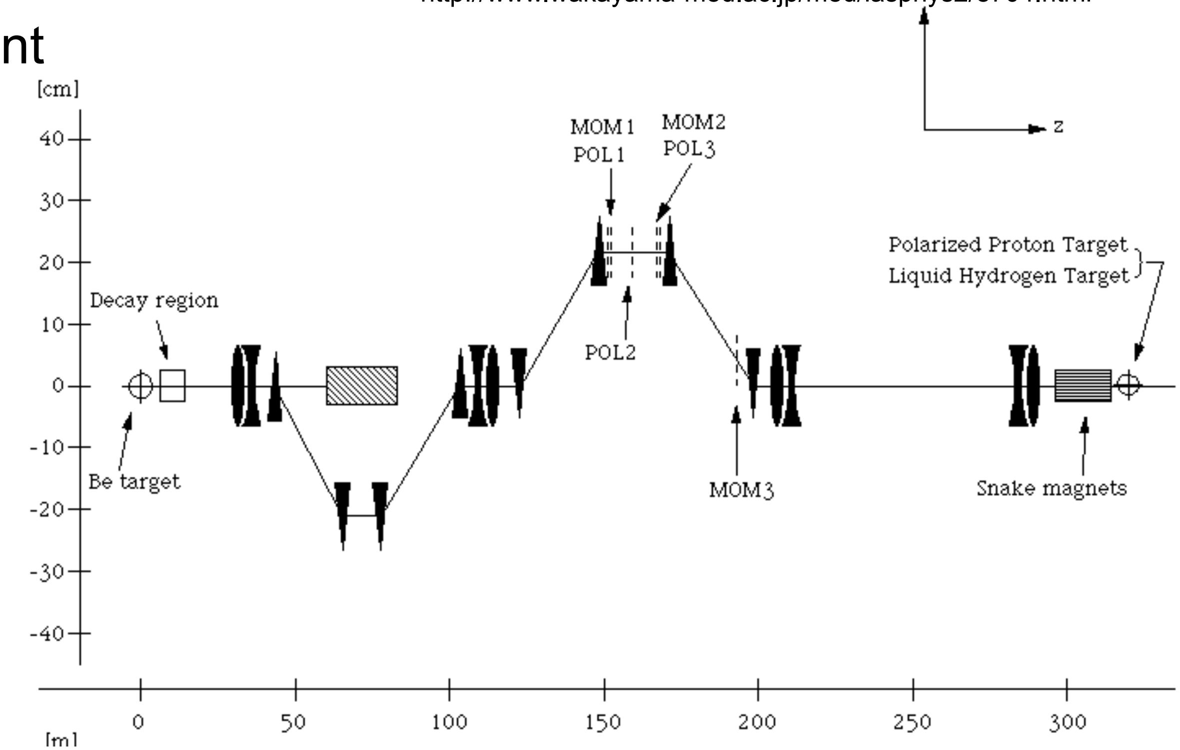
Hadroproduction

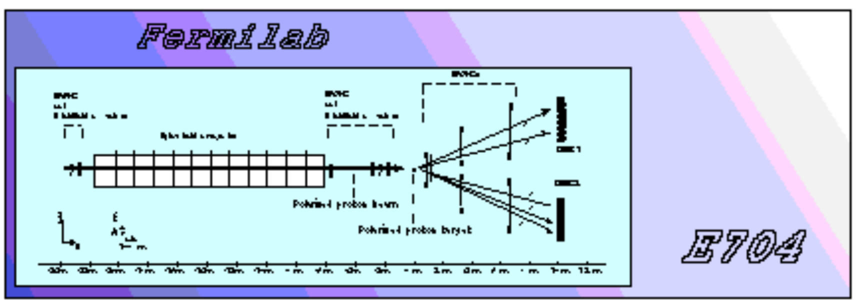
Past to Present

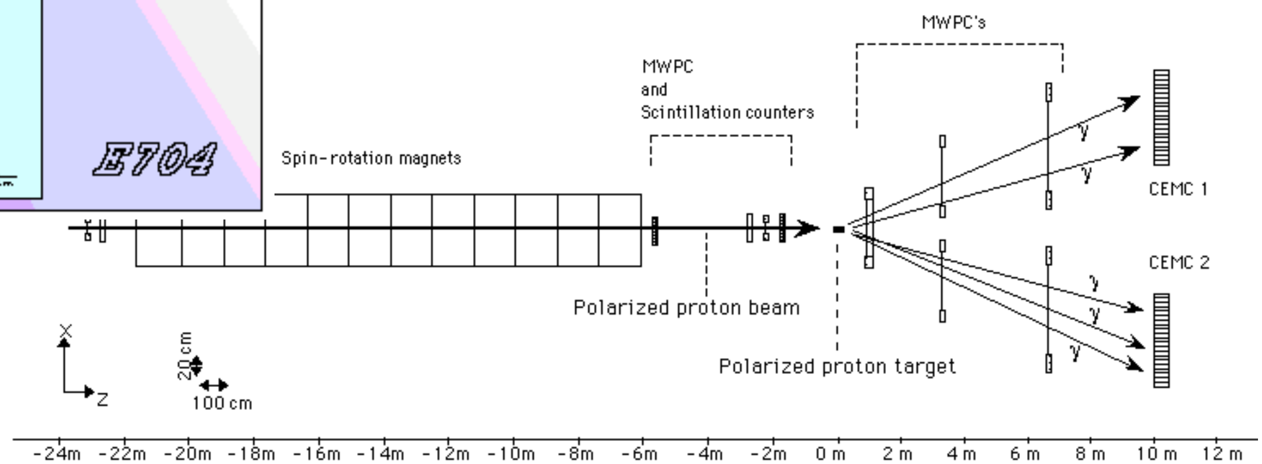
Virtual thanks to Seiji Makino

http://www.wakayama-med.ac.jp/med/lasphys2/e704.html

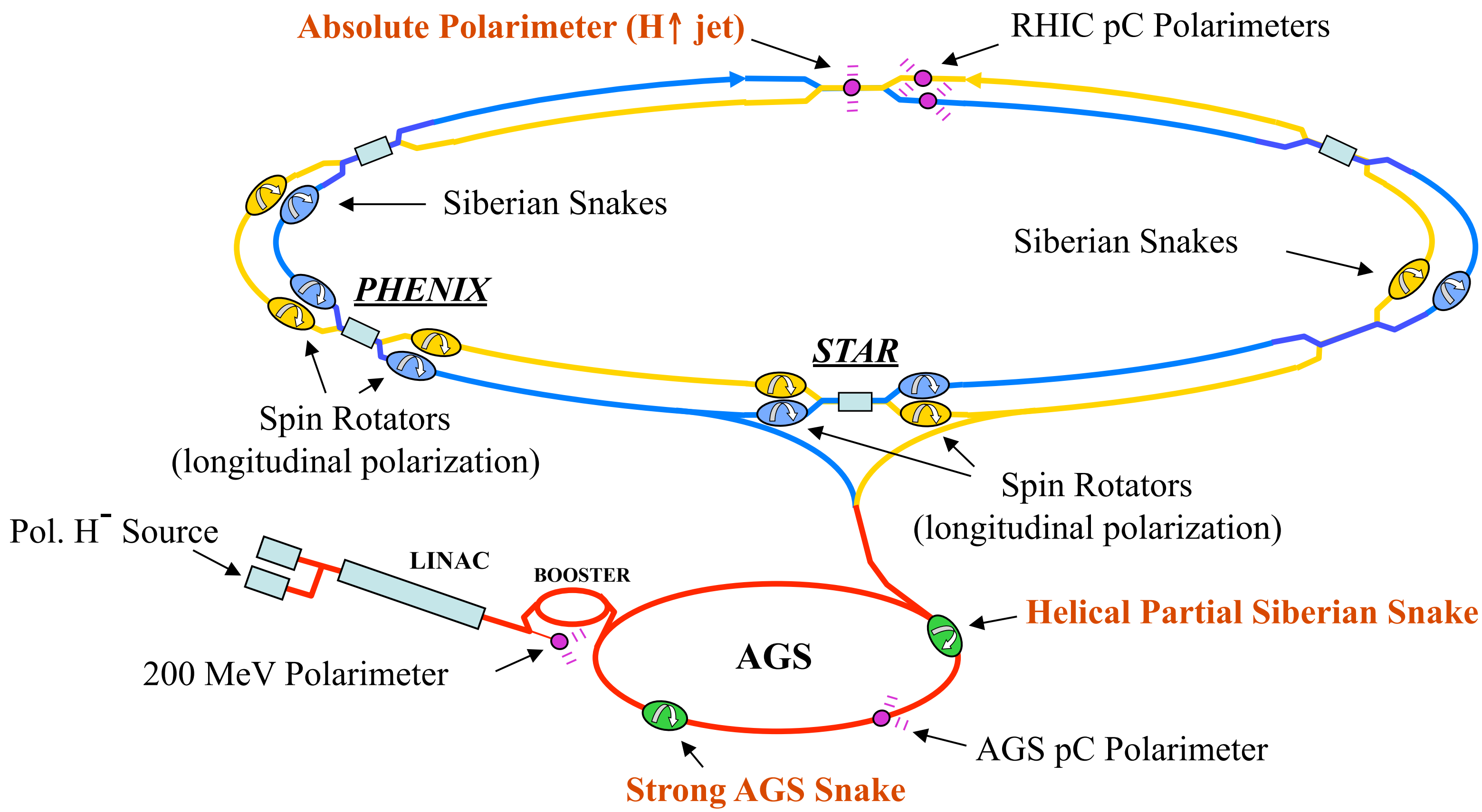
Using Λ polarization, produced in unpolarized collisions, to make a 200 GeV/c polarized proton beam.







RHIC is the First (Only) Polarized Proton Collider

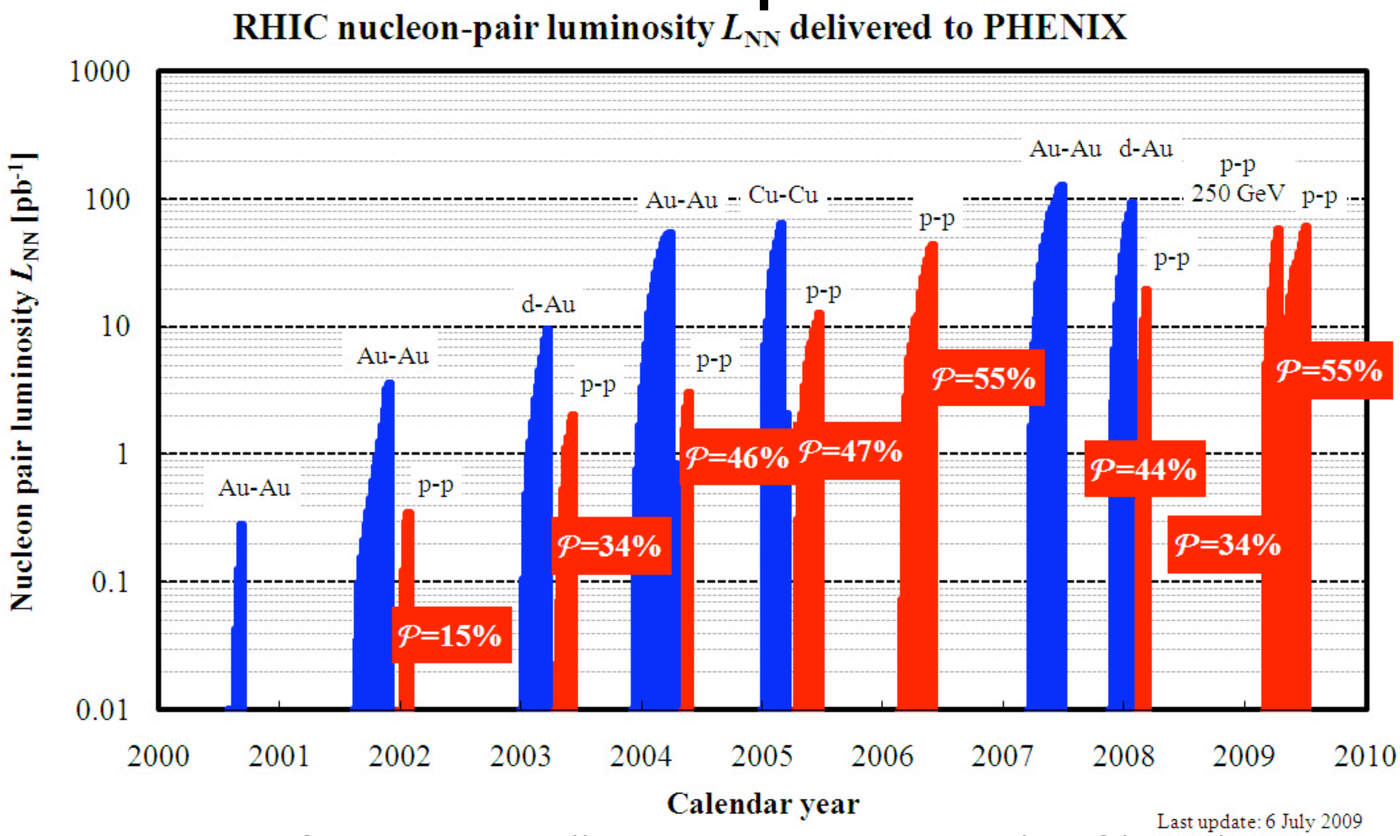


GOALS

reference: RHIC Spin Plan (2008) http://spin.riken.bnl.gov/rsc/report/spinplan_2008/spinplan08.pdf

- *Determination* of polarized gluon distribution (ΔG) *using multiple probes*
- *Determination* of flavor identified *anti-quark polarization* using *parity violating production of* $W^{\pm}$
- *Transverse spin:* connections to partonic orbital angular momentum (L_y) and transversity ($\delta\Sigma$)

RHIC is a Unique Collider…



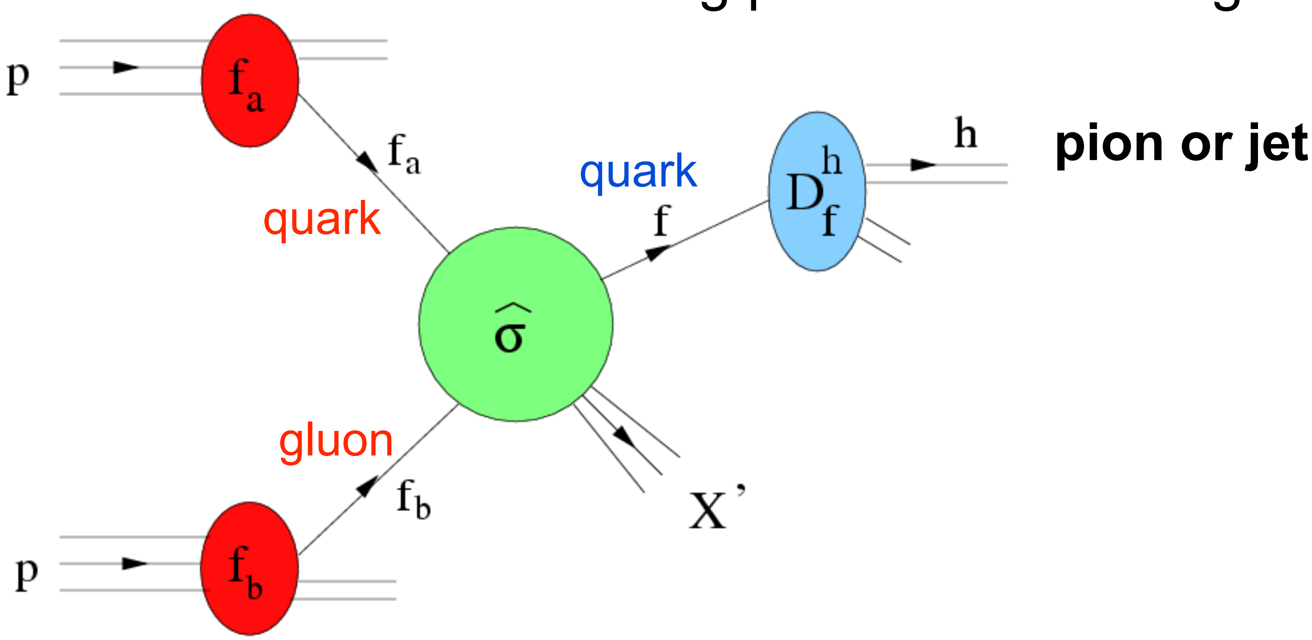
Source: http://www.agsrhichome.bnl.gov/RHIC/Runs/

- …capable of colliding essentially all positive ions over a broad range of √s
- …with large L/√s, where L is free space at interaction region ⇒ large x_F possible
- …with a broad and diverse physics program aimed at important questions
  - What is quark-gluon plasma? ⇒ heavy-ion collisions
  - How does the proton get its spin? ⇒ polarized proton collisions
  - Does the gluon density saturate in a heavy nucleus? ⇒ d+Au/p+Au collisions

RHIC Hard-Scattering Probes

⇒ Polarized proton collisions / hard scattering probes of ΔG

⇒ d+Au collisions / hard scattering probes of nuclear gluon density

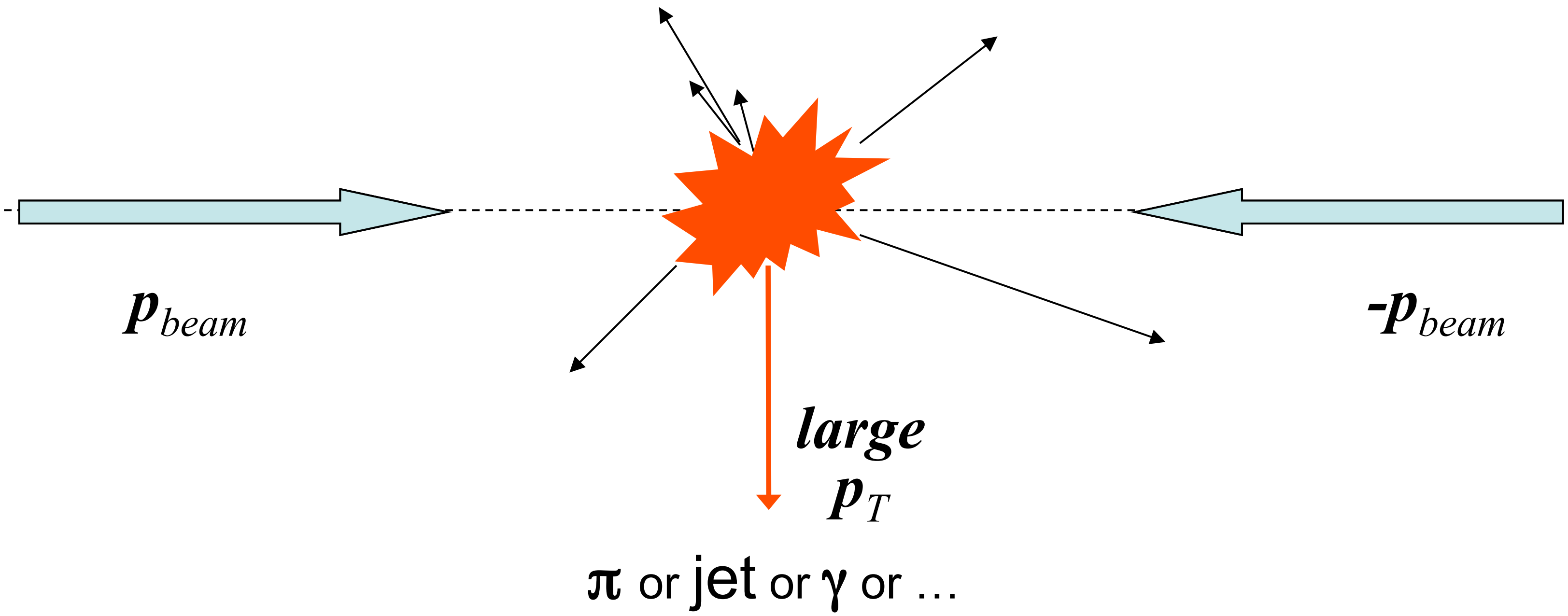


$$d\sigma_\pi = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \; f_a(x_a) f_b(x_b) D_c^\pi(z_c) d\hat{\sigma}_{ab}^c$$

Describe p+p particle production at RHIC energies ($\sqrt{s} \geq 62$ GeV) using perturbative QCD at Next to Leading Order, relying on *universal parton distribution functions and fragmentation functions*

Kinematics

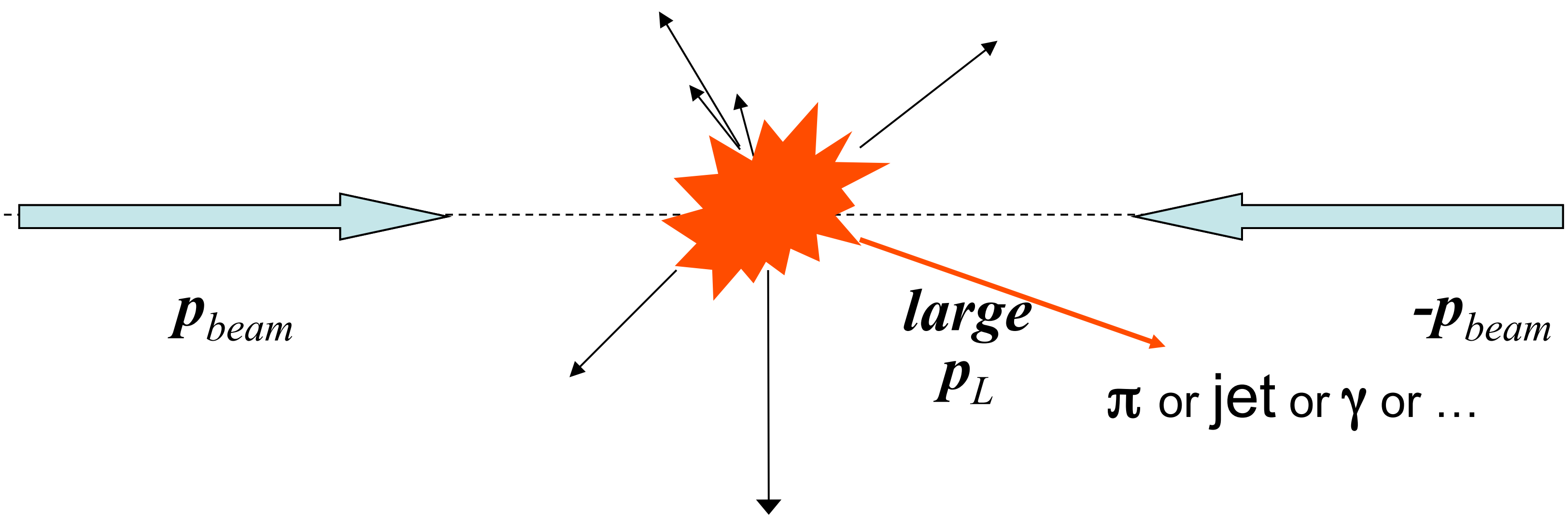
large-p_T physics in p+p collisions



Largest p_T reached by detecting produced particles at ϑ ~ 90° (midrapidity, η~0)

Kinematics

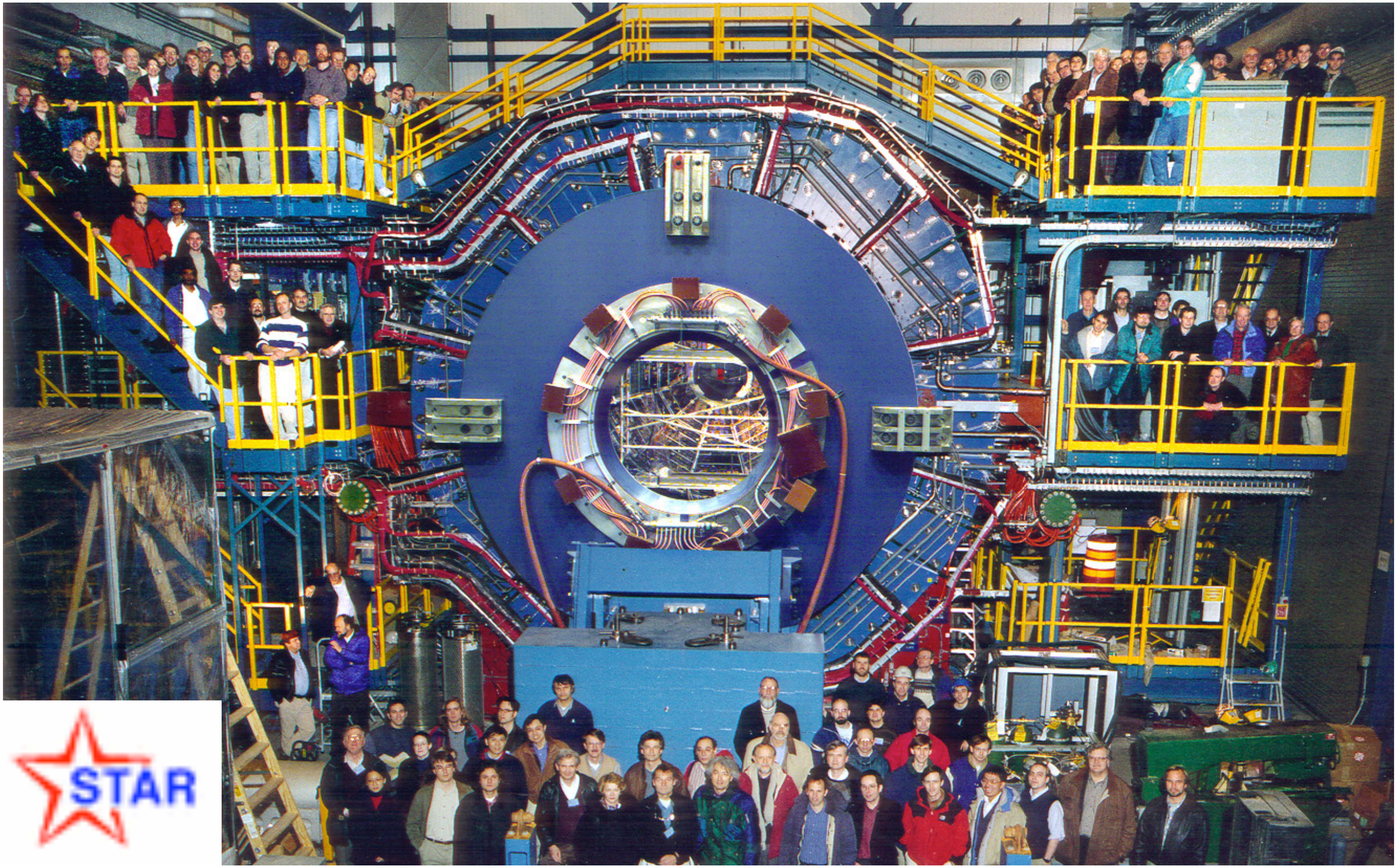
large-x_{F} (with sufficient p_{T}) physics in p+p collisions



Large $\boldsymbol{p}_L$ (produced particle at large η) is required to reach large Feynman-x,

$$x_{\mathrm{F}} = p_L \,/\, p_{beam} = 2\, p_L \,/\, \sqrt{s}$$

STAR



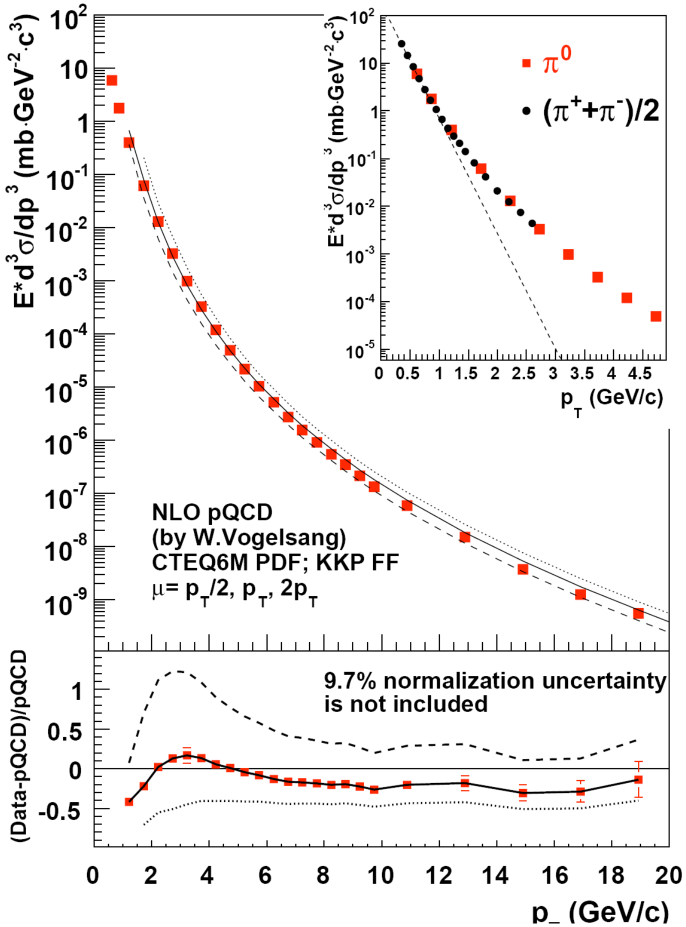
Three stories of exceptional mid-rapidity coverage and a unique window for a collider

RHIC Probes

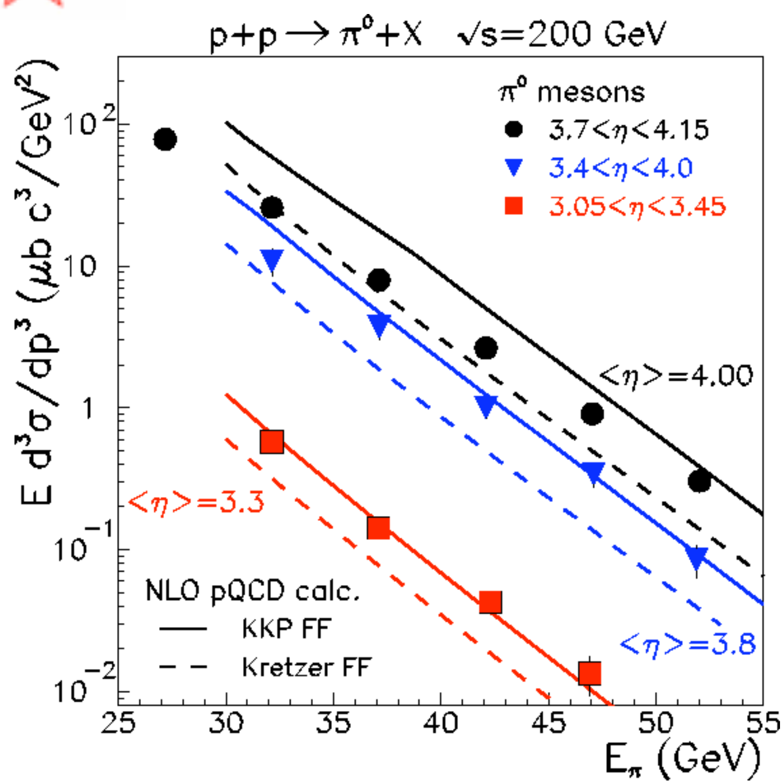
Unpolarized cross sections as benchmarks and heavy-ion references

$p + p \rightarrow \pi^0 + X, \sqrt{s} = 200$ GeV

PHENIX PRD 76 (2007) 051106



STAR PRL **92** (2004) 171801

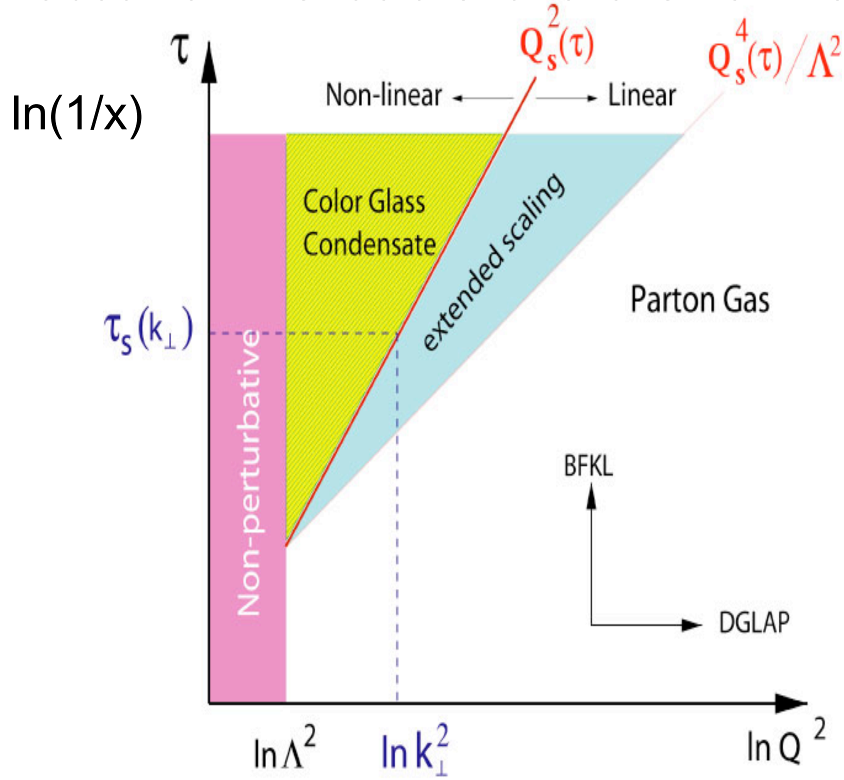


Good agreement between experiment and theory

⇒ calibrated hard scattering probes of proton spin and low-x gluons

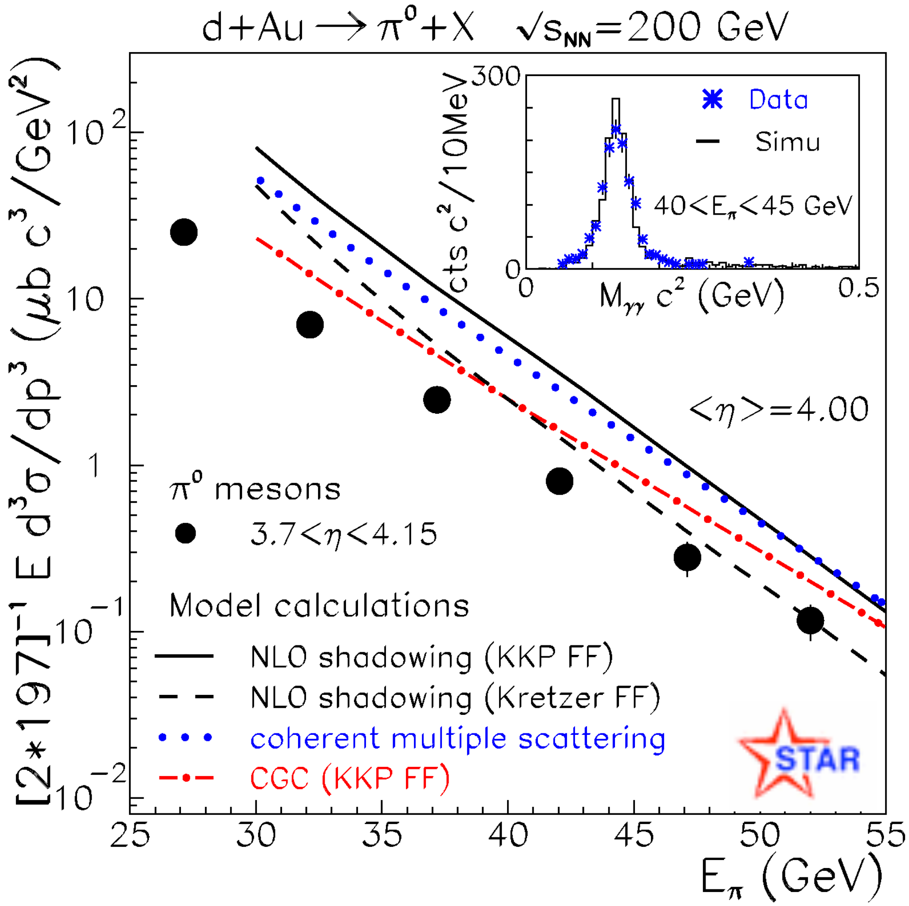
Goals II

- How does the proton gets its spin from quarks and gluons?
- Where do conventional descriptions of particle production (e.g., perturbative QCD) apply?
- Are there new things to learn about partonic substructures at large x?
- Can we learn about low-x structure functions from hadronic interactions?



Edmond Iancu and Raju Venugopalan, Review for Quark Gluon Plasma 3, R.C. Hwa and X.-N. Wang (eds.), World Scientific, 2003 [hep-ph/0303204].

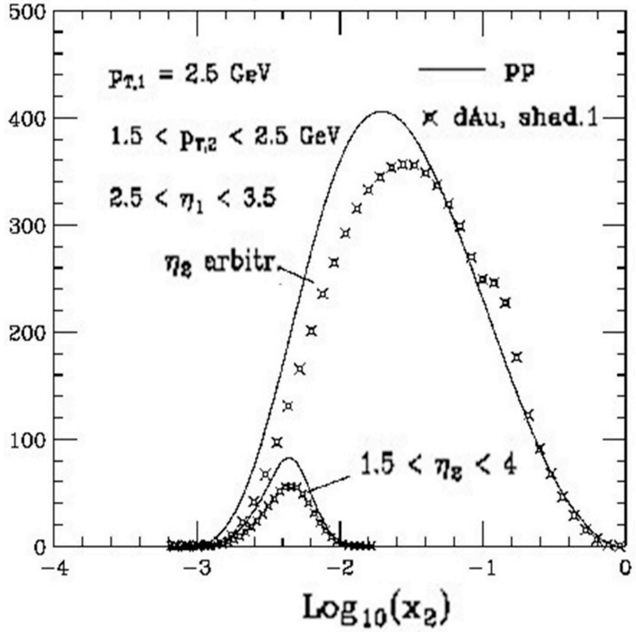
Inclusive π^0 production from dAu



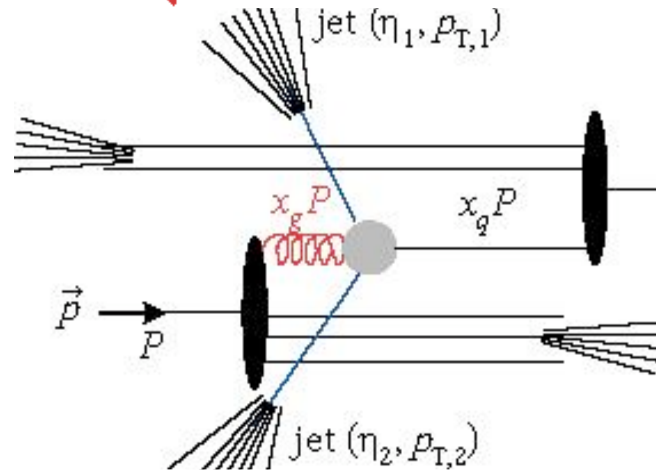
J. Adams *et al.* (STAR), PRL **97** (2006) 152302

Particle production cross sections for d+Au collisions are smaller than expectations from only shadowing at <η> =4.0, and the energy dependence is best described by CGC calculations (A. Dumitru et al. Nucl Phys A765 (2006) 464)

Guzey, Strikman and Vogelsang
Phys. Lett. B603 (2004) 173

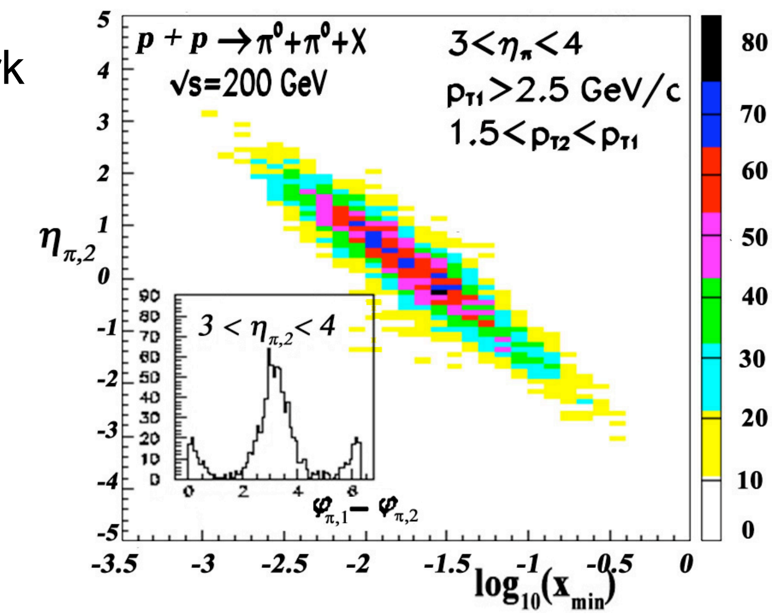


$$x_+ \approx \frac{p_T}{\sqrt{s}}\left(e^{+\eta_1} + e^{+\eta_2}\right) \xrightarrow[\eta_1 >> \eta_2]{} x_F$$



$$x_- \approx \frac{p_T}{\sqrt{s}}\left(e^{-\eta_1} + e^{-\eta_2}\right) \xrightarrow[\eta_1 >> \eta_2]{} x_F e^{-(\eta_1 + \eta_2)}$$

- constrain x value of gluon probed by high-x quark by *detection of second hadron* serving as jet surrogate.
- span broad pseudorapidity range (-1<η<+4) for second hadron ⇒ span broad range of x_{gluon}
- provide sensitivity to higher p_T for forward π^0 ⇒ reduce 2→3 (inelastic) parton process contributions thereby reducing uncorrelated background in Δϕ correlation.

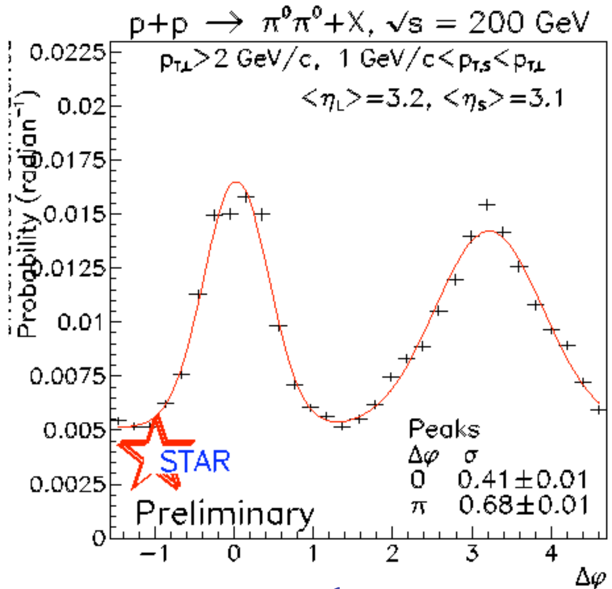


PYTHIA Simulation

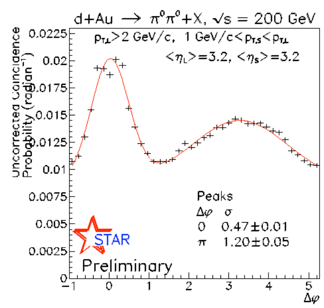
[hep-ex/0502040]

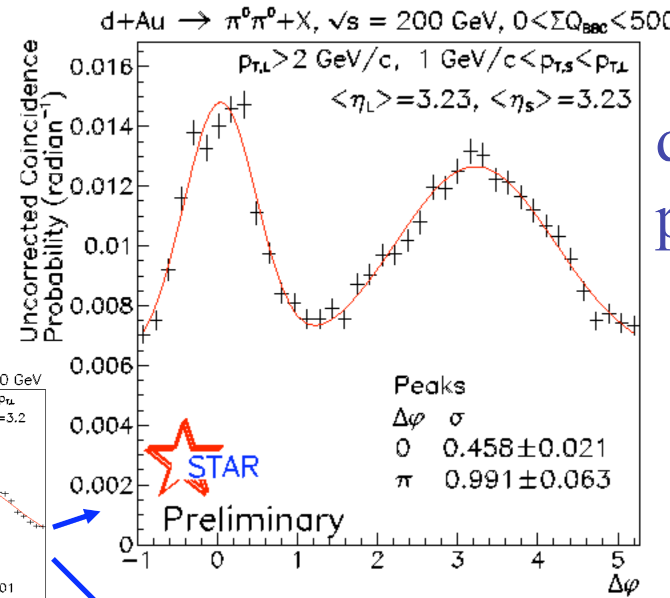
Centrality dependence of forward di-pion decorrelation

Leading P_T pion > 2.0 GeV

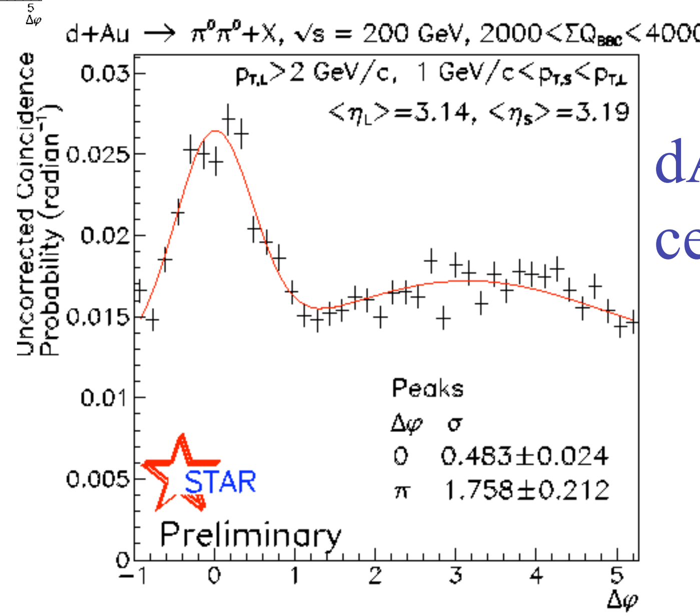


pp data





dAu peripheral



dAu central

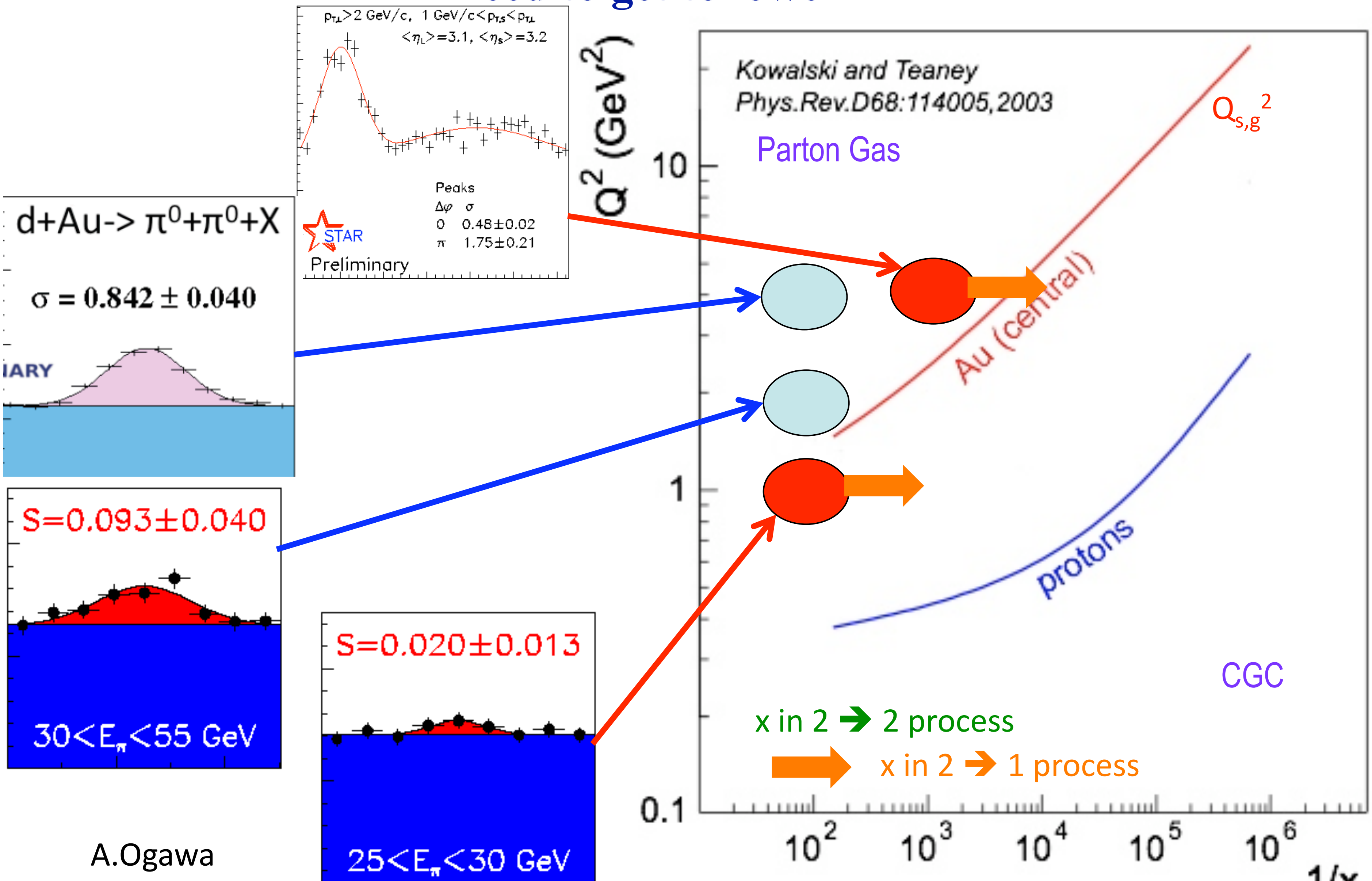
Away-side peaks evident in peripheral dAu and pp.

Away-side peaks in peripheral dAu are roughly 50% wider than in pp.

Significant dependence on centrality is evident in azimuthal decorrelation.

Mapping Saturation Scales

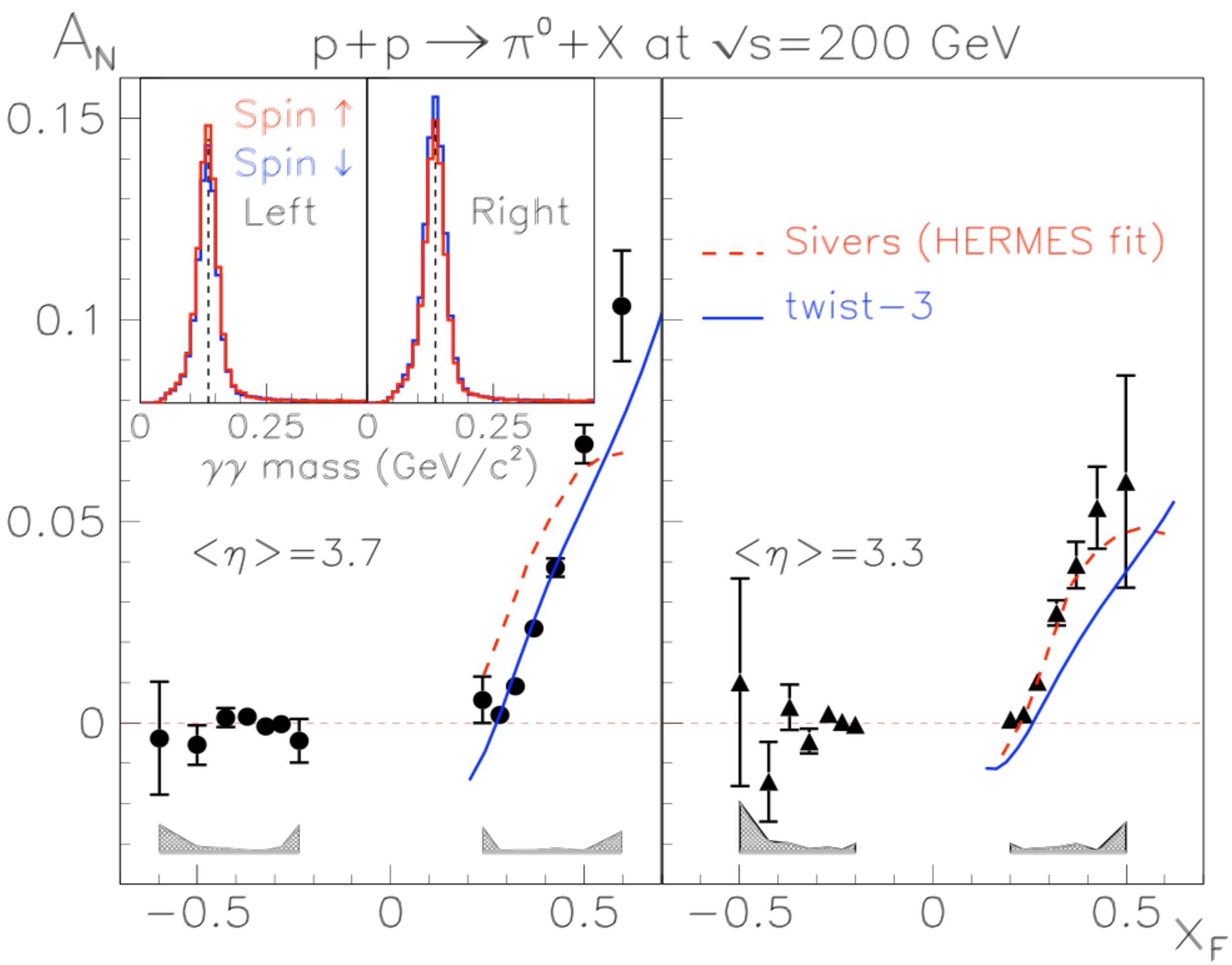
need to get to lower x



A.Ogawa

x_F Dependence of Inclusive π^0 A_N

RHIC Run 6 with FPD/FPD++



PRL 101, 222001 (2008)
arXiv:0801.2990 [hep-ex]

Fits to SIDIS (HERMES) is consistent with data

A_N at positive x_F grows with increasing x_F

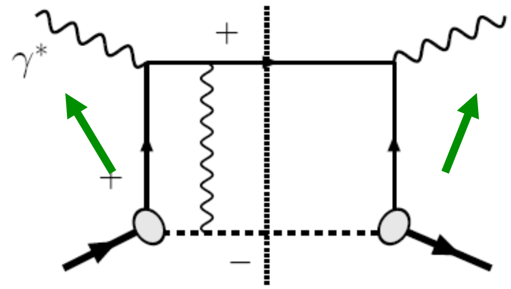
U. D'Alesio, F. Murgia
Phys. Rev. D 70, 074009 (2004)
arXiv:hep-ph/0712.4240

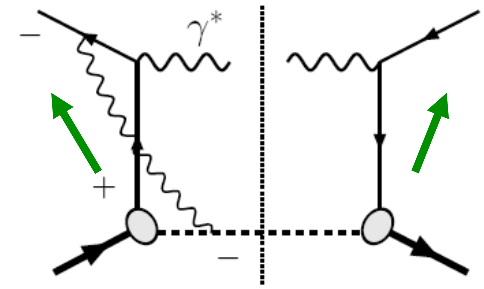
C. Kouvaris, J. Qiu, W. Vogelsang, F. Yuan,
Phys. Rev. D 74, 114013 (2006).

Attractive vs Repulsive Sivers Effects

Unique Prediction of Gauge Theory !

Simple QED example:

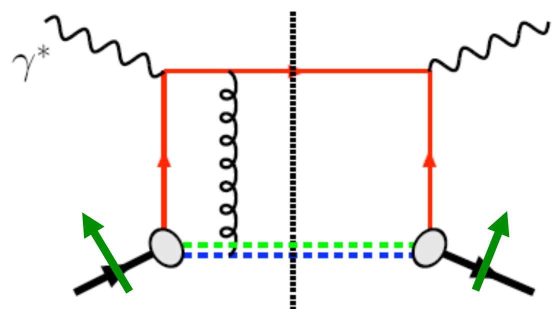


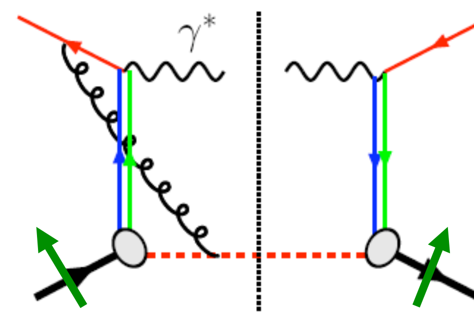


DIS: attractive

Drell-Yan: repulsive

Same in QCD:





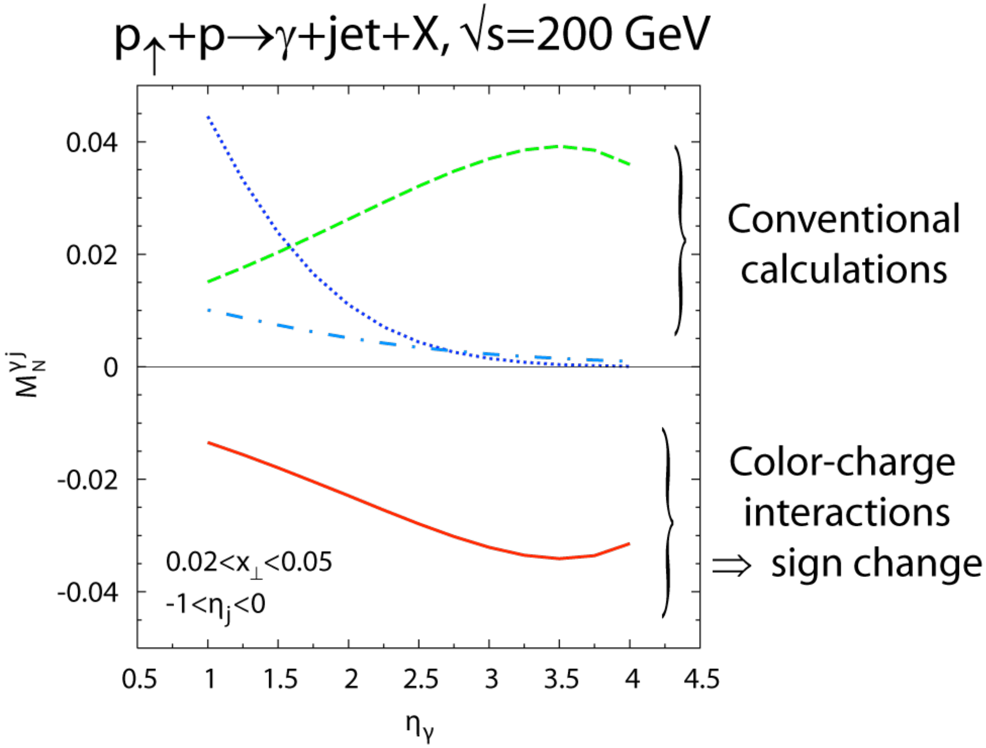
As a result:

$$\boxed{\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}}$$

Transverse Spin Drell-Yan Physics at RHIC (2007)

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Transverse spin direct γ



Theory expects repulsive color charge interactions to result in an opposite sign to spin-correlated momentum imbalance for γ+jet.

Bacchetta et al., PRL 99, 212002
also Kouvaris,Qiu,Vogelsang and Yuan
and, Teryaev and Ratcliffe

- Estimate that sign change is accessible with L_{int} = 30 pb^{-1} and P_{beam}=0.65
- Best done at $\sqrt{s}$ = 200 GeV for π^0 / γ separation
- Best done before removal of STAR Forward TPC

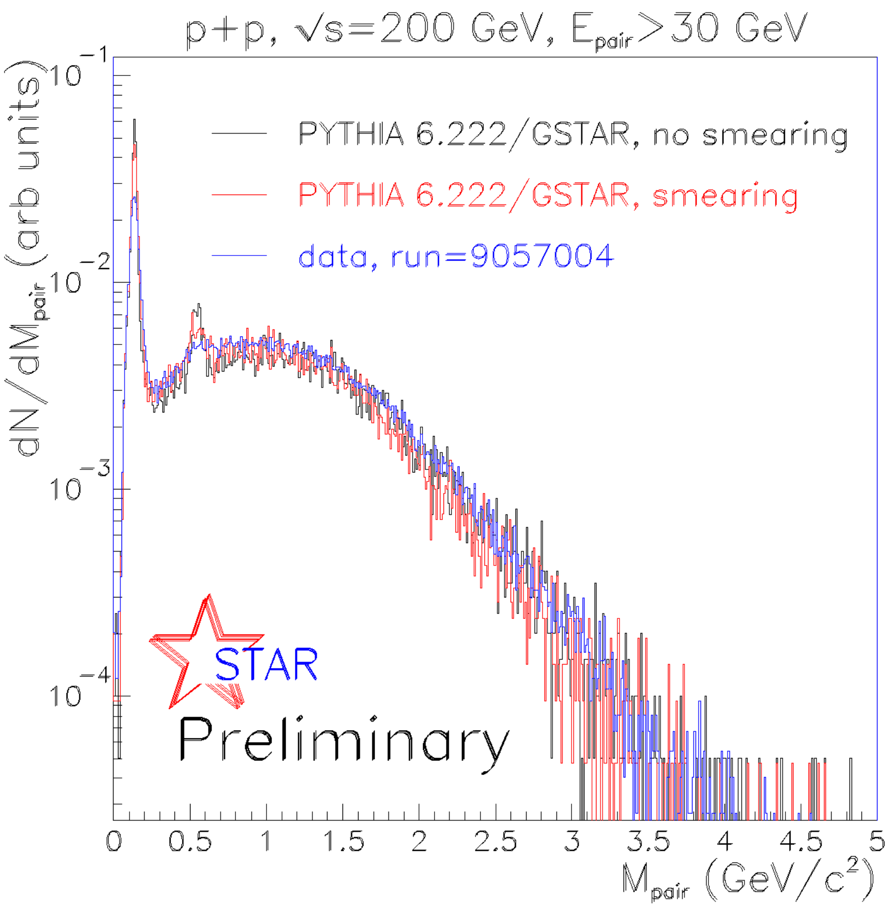
As part of the 2008 update to *Plans for the RHIC Spin Physics Program*

Status

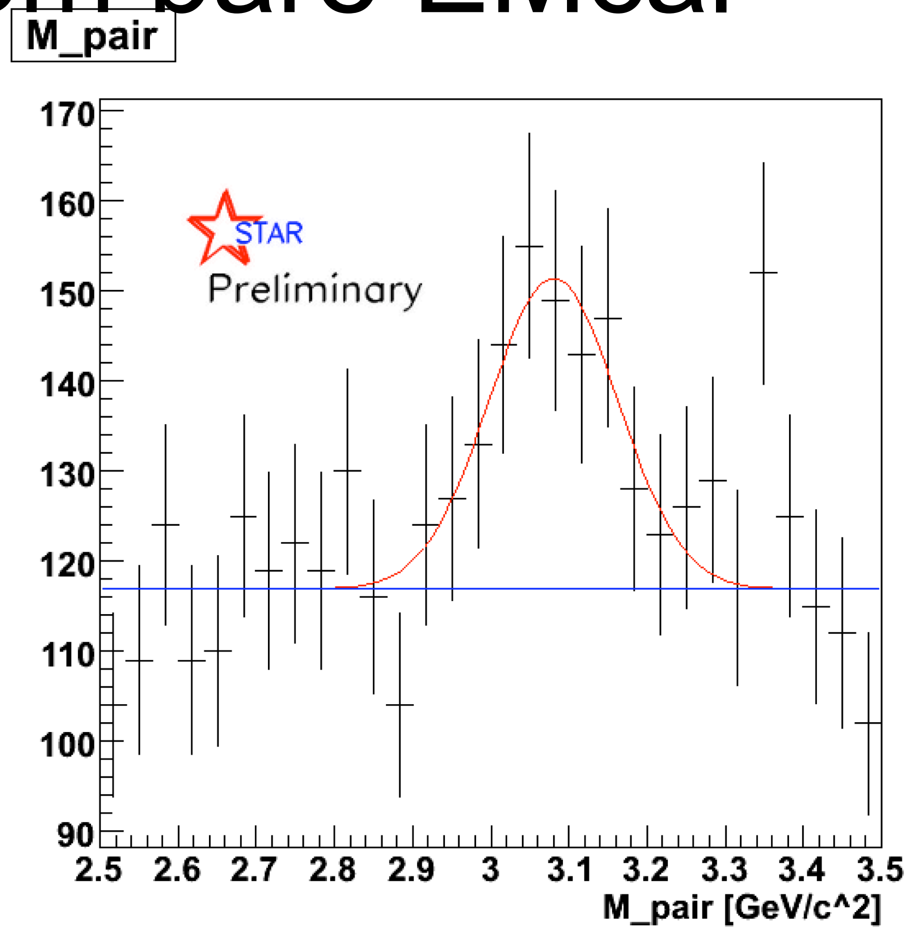
- Luminosity gains projected for $\sqrt{s}$=200 GeV polarized proton collisons were not realized, so L_{int}=30 pb^{-1} and P_{beam}=65% for transverse spin direct photon would be challenging.
- Theory community has revisited whether color-charge interactions are robustly calculable [arXiv:1001.2977] for transverse single-spin asymmetries for processes *other than Drell Yan production*
- Low-x/saturation physics looks to be very interesting at RHIC collision energies. Non-universality of k_T dependent distribution functions for di-jets may impact small-x as well as transverse spin [arXiv:1003.0482]. This should not be the case for *low-x probed by Drell-Yan production*

$\Rightarrow$ establishing the requirements for a large-x_F Drell Yan production experiment will provide the most robust test of theory for transverse spin, and lead to future avenues that provide the most robust interconnections between low-x probed at RHIC and low-x probed at eRHIC.

Pair mass from bare EMcal



arXiv:0906.2332



arXiv:0907.4396

- pair mass backgrounds well modeled
- J/ψ→e+e- observation at <xF>~0.67 emboldens DY consideration

Motivations for DY Feasibility at IP2

2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering

Report to NSAC from the Subcommittee on Performance Measures (August, 2008)
http://www.sc.doe.gov/np/nsac/docs/PerfMeasEvalFinal.pdf

- **Timeliness** – HP13 milestone completion by 2015. This could be accomplished during W program if 3IR impact is acceptable.
- **Acceptance/background rejection** – severe space constraints at STAR and PHENIX require major changes in the forward direction. Space constraints are not present at IP2.
- **Is charge sign a requirement?**

Objective of DY feasibility test is to establish the **requirements for future major forward upgrades at STAR and PHENIX** that would be used in a future p+Au or d+Au run that would emphasize Drell Yan production to probe low-x through scaling violations or virtual photon p_T dependence.

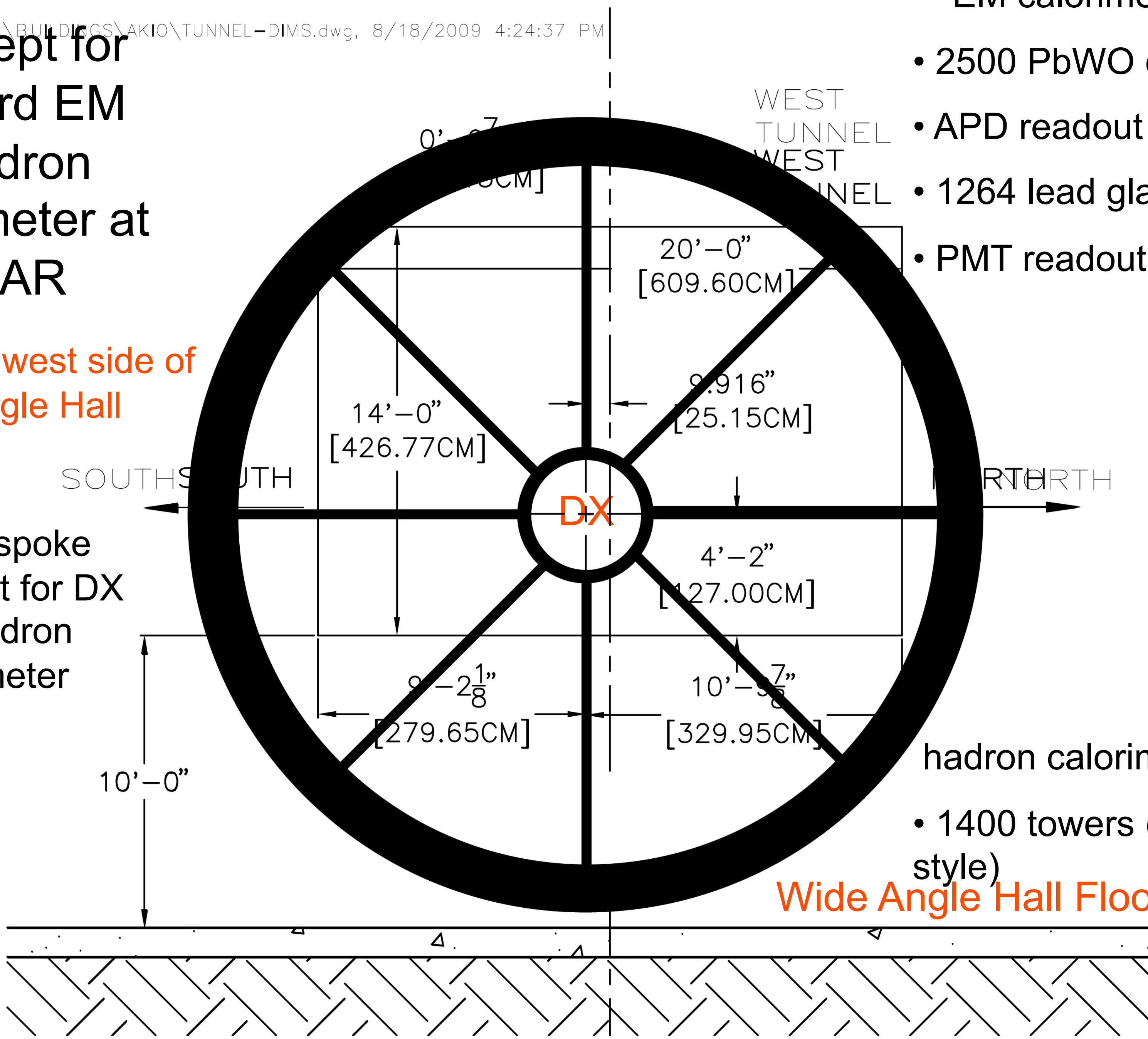
Requirements for DY
Background Reduction

- electron/hadron discrimination / Q. What hadronic suppression required?
- Charged/Neutral discrimination and photon conversion background
- Is charge sign discrimination required for like-sign pair subtraction?

Concept for forward EM +hadron calorimeter at STAR

Existing west side of Wide Angle Hall

wheel/spoke support for DX and hadron calorimeter



EM calorimeter…

- 2500 PbWO crystals
- APD readout
- 1264 lead glass
- PMT readout

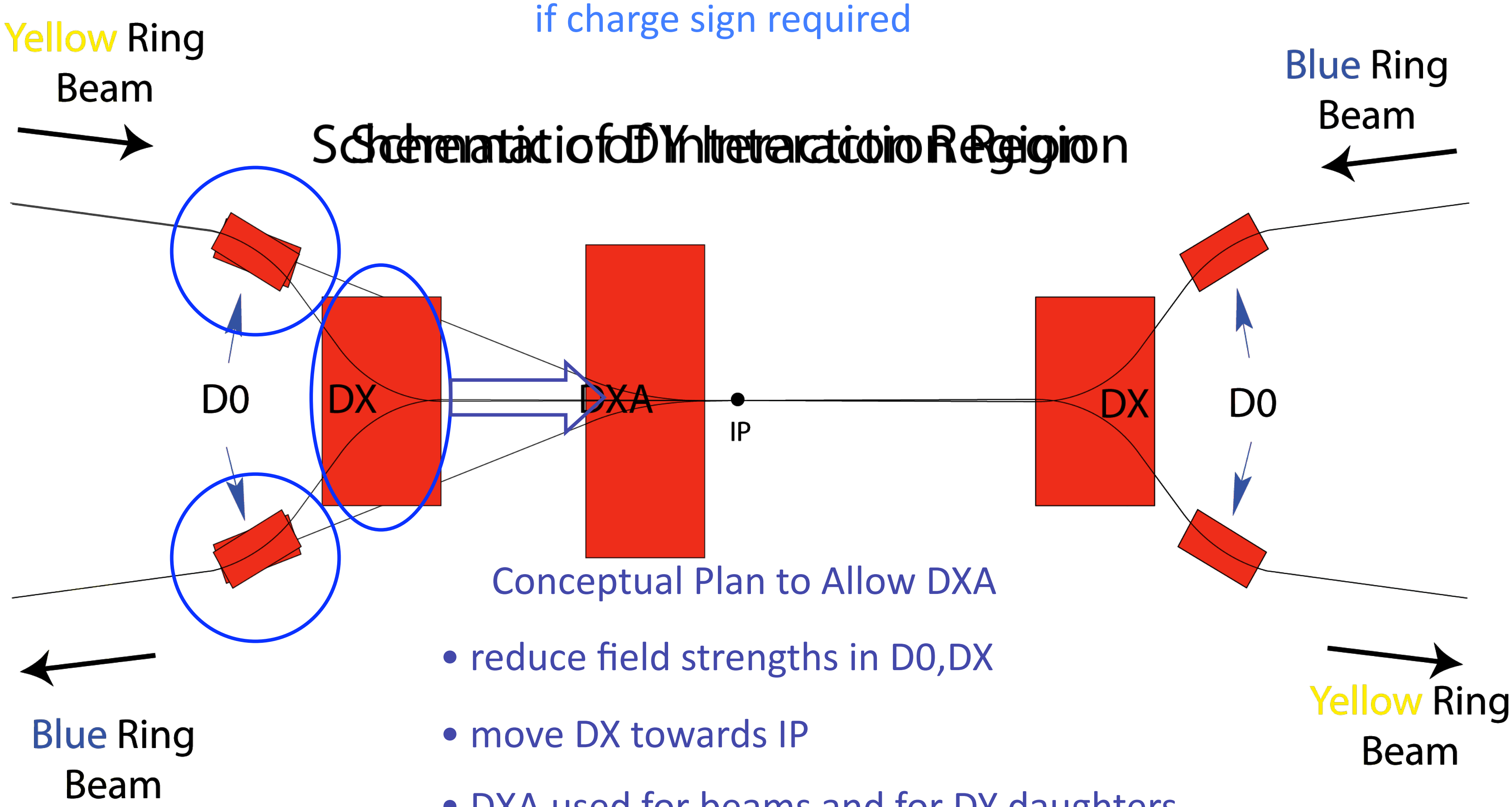
hadron calorimeter…

- 1400 towers (Atlas-style)

Dipole Analysis Magnet Concept

Forward DY Interaction Region

if charge sign required



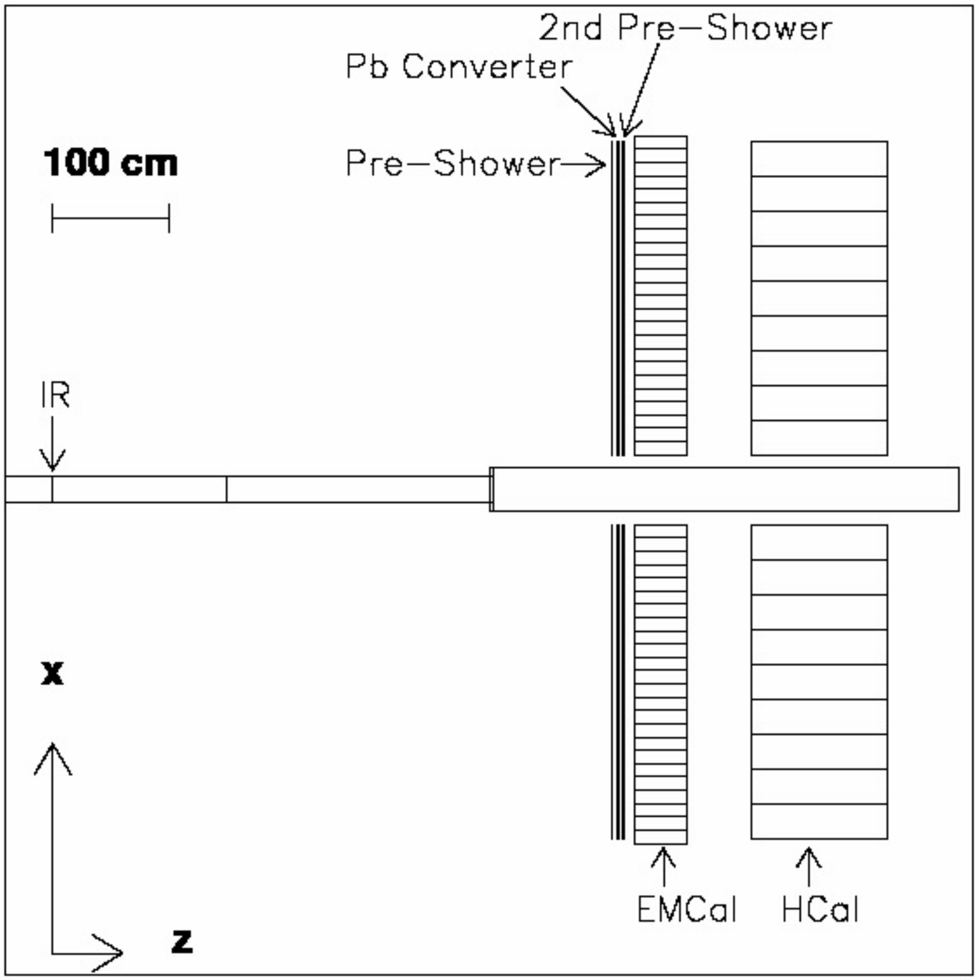
Conceptual Plan to Allow DXA

- reduce field strengths in D0,DX
- move DX towards IP
- DXA used for beams and for DY daughters

Schematic of detector considered

Run-12 configuration

(PHOBOS split-dipole expected to be in place, but not used)

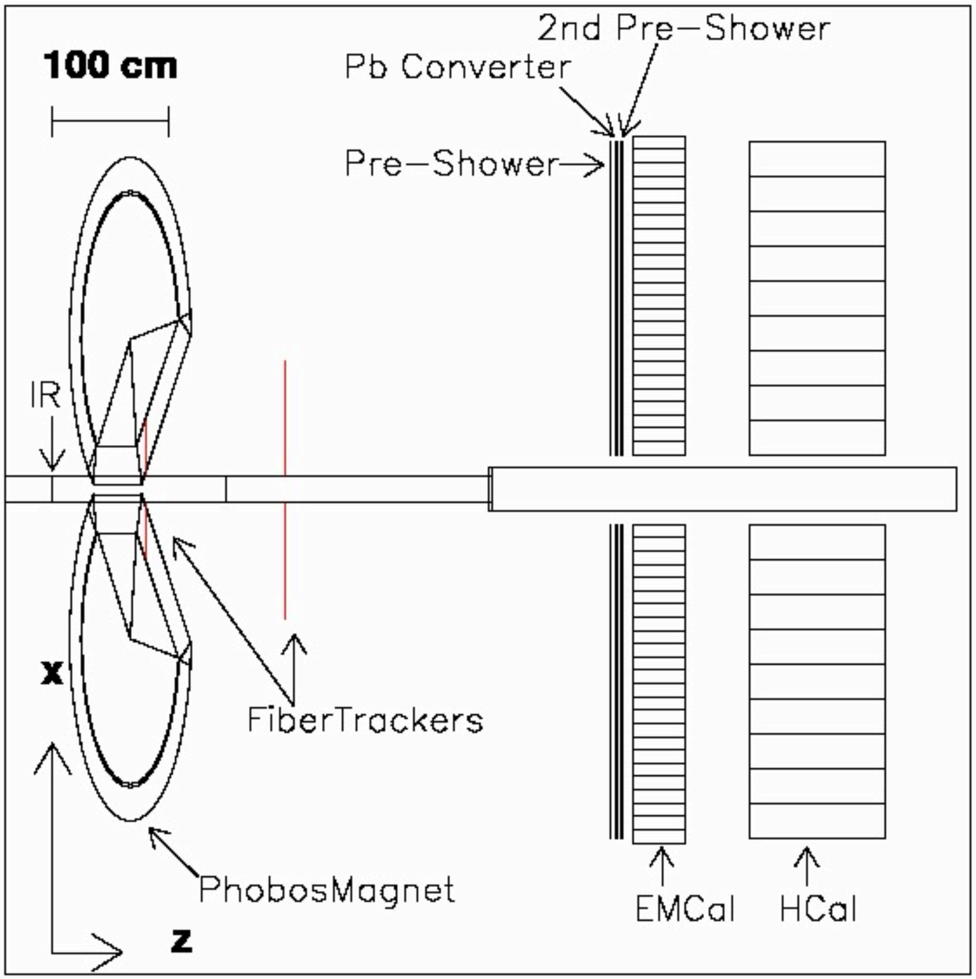


http://www.star.bnl.gov/~akio/ip2/topview2.jpeg

- Hcal is existing 9x12 modules from E864 (NIM406,227)
- EMcal is modeled as only $(3.8cm)^2 x (45cm)$ lead glass
- Preshower would require construction

Schematic of detector considered

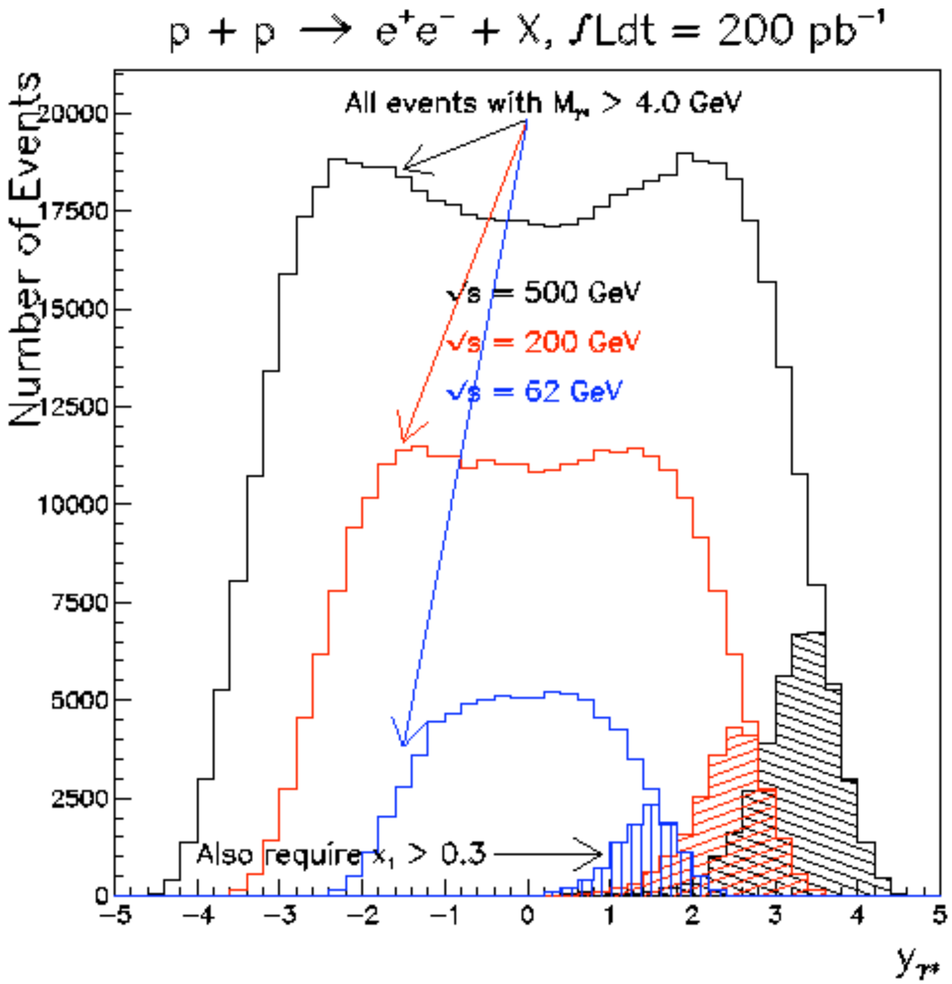
Run-13 configuration
(Uses PHOBOS Split Dipole for charge sign)



- Hcal is existing 9x12 modules from E864 (NIM406,227)
- EMcal is modeled as only $(3.8cm)^2x(45cm)$ lead glass
- Preshower would require construction
- PHOBOS split-dipole magnetic field in GEANT model
- Fiber tracker stations require specifications and construction

http://www.star.bnl.gov/~akio/ip2/topview3.jpeg

Collision Energy Dependence of Drell Yan Production



Comments…

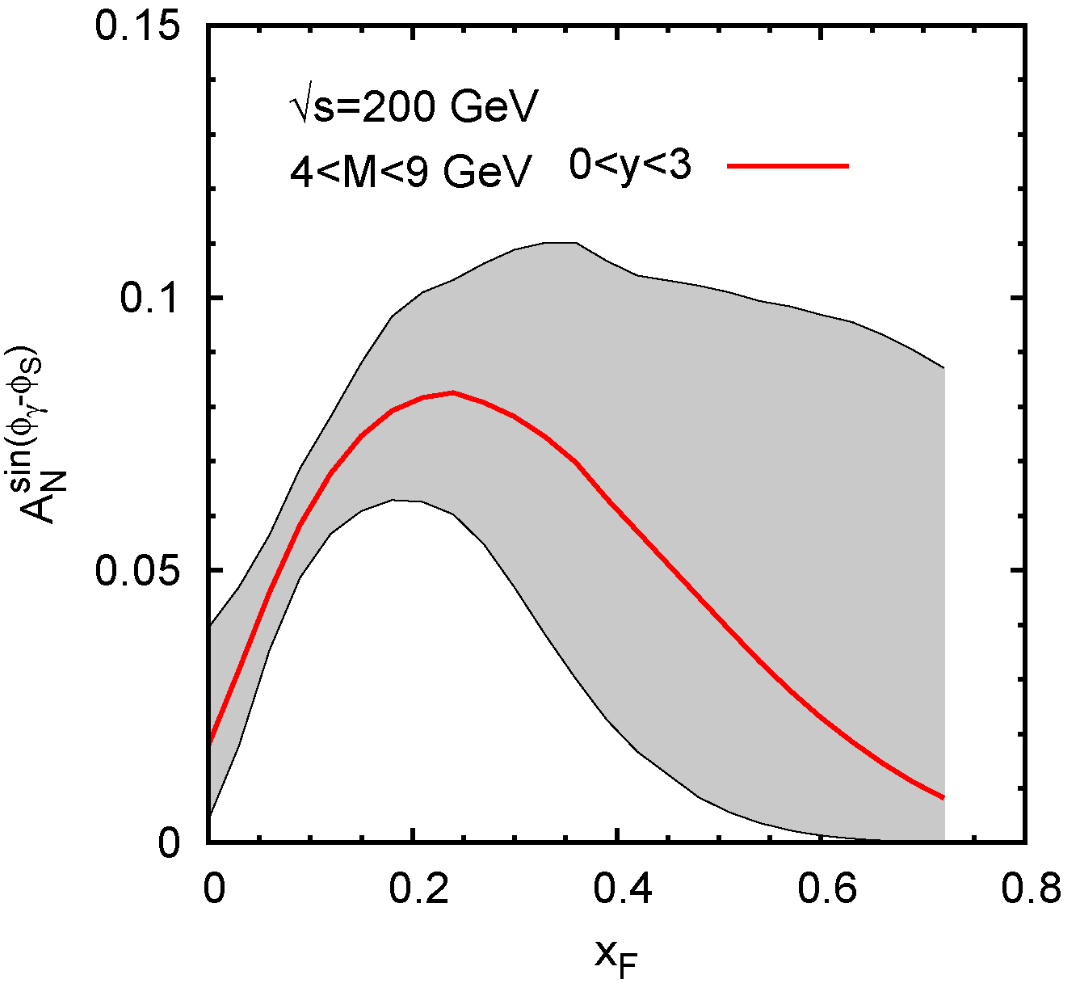
- $\bar{q}q \rightarrow \gamma^{*}$ has $\hat{\sigma} \propto 1/\hat{s}$
- partonic luminosities increase with √s
- net result is that DY grows with √s
- in any case, largest √s probes lowest x

⇒ Consider large-x_F DY at √s=500 GeV

Transverse Spin Drell-Yan Physics at RHIC (2007)

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

DY Expectations



- Non-zero A_N expected at moderate to large x_F
- Measurement with accuracy $\delta A_N<0.02$ should be of great interest
- With P_{beam}=50%, require 10K events for $\delta A_N=0.02$
- Uses Sivers function from EPJ A39 (2009) 89, that fits preliminary HERMES results and COMPASS deuteron results
- $\sqrt{s}$=500 GeV predictions very similar, since $x_F=x_1-x_2$ is the relevant parameter (private communication)

Anselmino, et al PRD 79 (2009) 054010 [arXiv:0901.3078]

Previous Work

p+p DY at ISR, √s=53,63 GeV
Phys. Lett. B91 (1980) 475

STUDY OF MASSIVE ELECTRON PAIR PRODUCTION AT THE CERN INTERSECTING STORAGE RINGS

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Received 18 February 1980

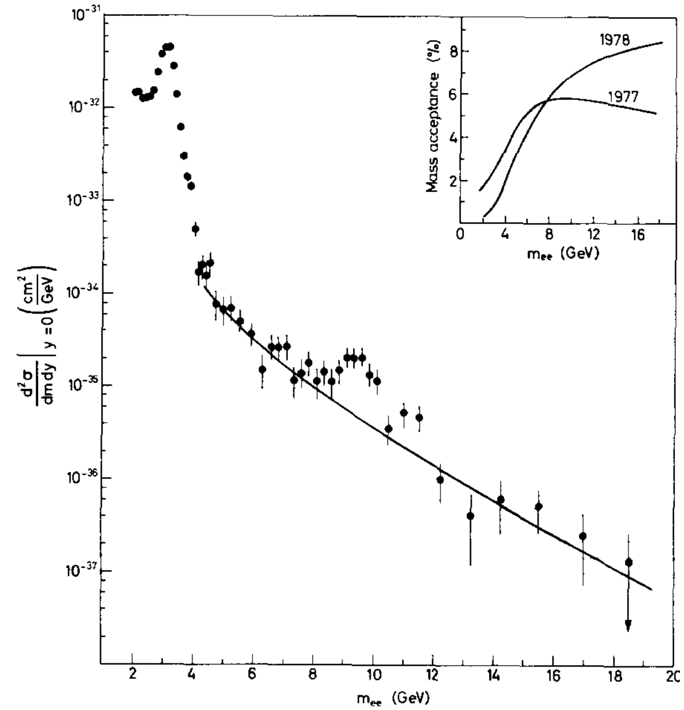
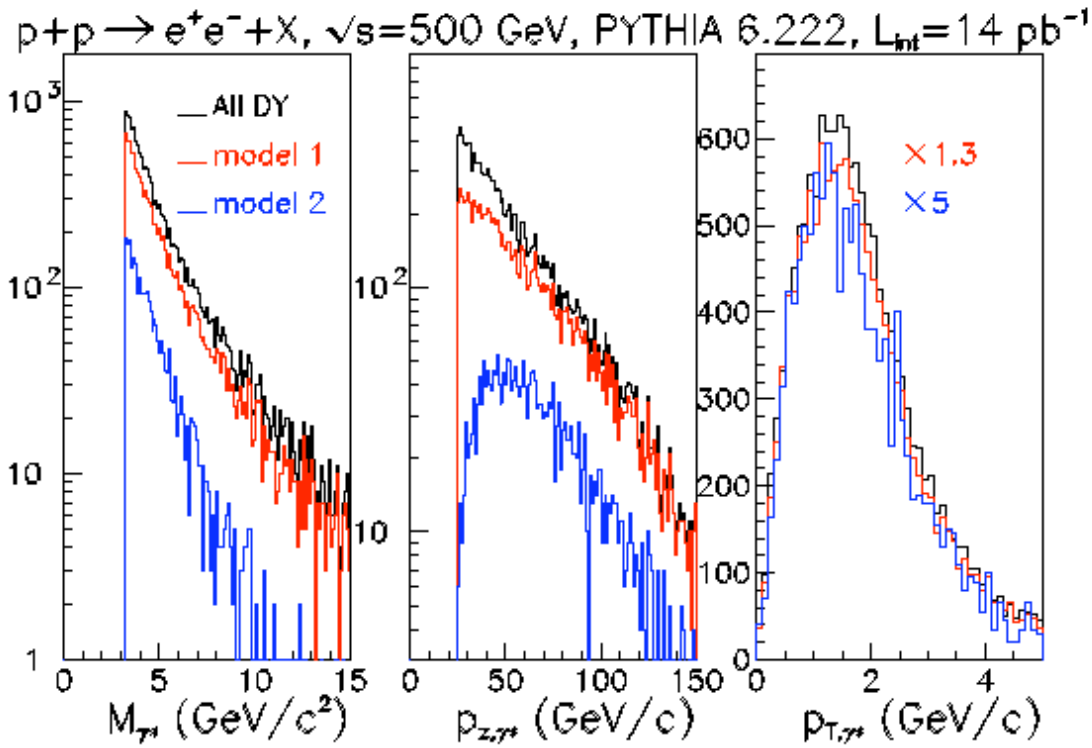


Fig. 1. The cross section $(d^2\sigma/dm\,dy)_{y=0}$ versus mass for the data at $\sqrt{s}$ = 53 and 63 GeV combined. The curve is a result of the fit to the continuum displayed in fig. 2. The inset show the mass acceptance for "1977" and "1978" triggers and geometrical configurations calculated for isotropic decay distributions and production uniform in rapidity with p_T dependence $d\sigma/dp_T^2 \sim \exp(-bp_T)$, where b = 1.4 GeV^{-1}. The mass acceptance changes by ± 15% when the helicity decay distribution follows $dN/d\cos\theta = 1 + \alpha\cos^2\theta$ when $\alpha = \pm 1$, where θ is measured in the s-channel helicity frame.

Comments (note: large x_F at collider breaks new ground)

- e+e- low-mass DY done at ISR and by UA2 [see review J.Phys. G19 (1993) D1]
- UA2 [PLB275 (1992) 202] did not use magnet / CCOR did [PLB79 (1979) 398]
- most fixed target experiments do $\mu^+\mu^-$ DY

e+e- DY expectations at large x_F at $\sqrt{s}$=500 GeV



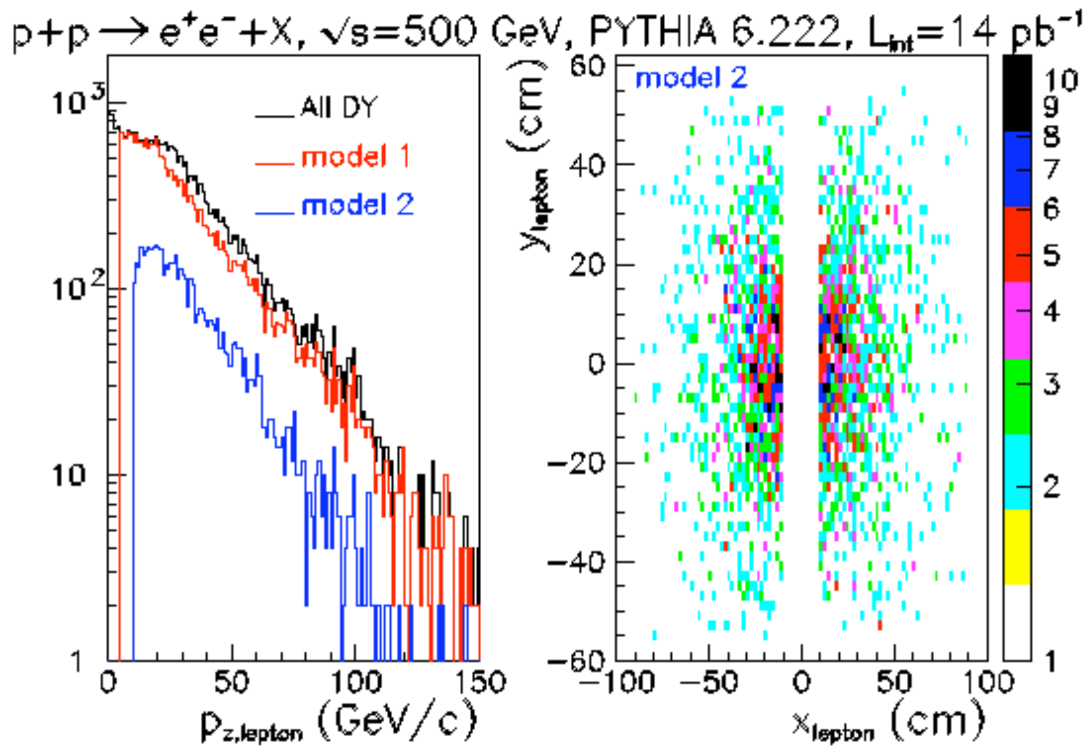
Model 1 = EMcal $(2m)^2$ / $(0.2m)^2$ beam hole at 10m / no magnetic field

Model 2 = L/R modular EMcal (0.9mx1.2m) at 5m / no magnetic field

Comments…

- reasonable efficiency can be obtained for large-x_F DY with existing equipment
- final estimates of DY yield must follow estimates of background rejection
- critical question for decadal planning: is charge sign discrimination required?

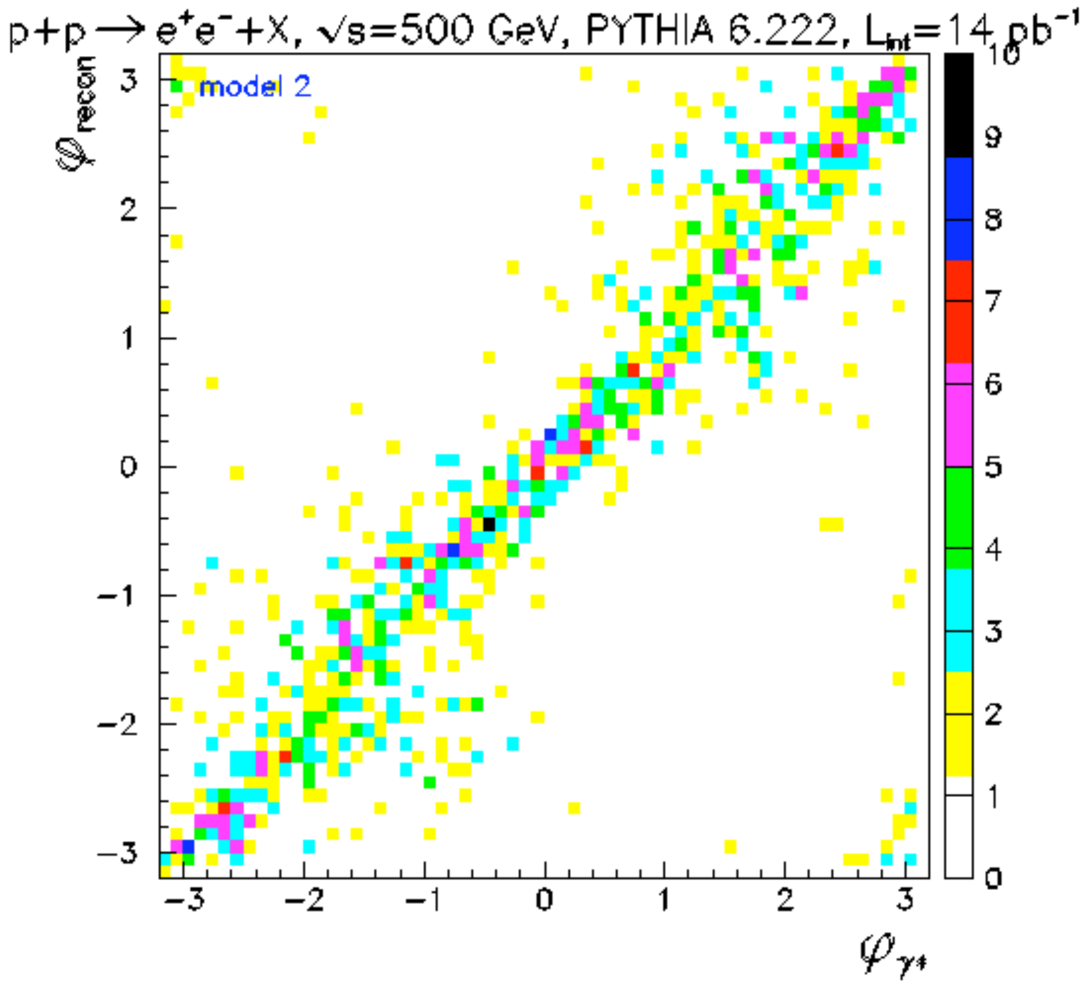
Lepton daughters from γ^*



Most important contributions for γ^* x_F>0.1 at √s=500 GeV …

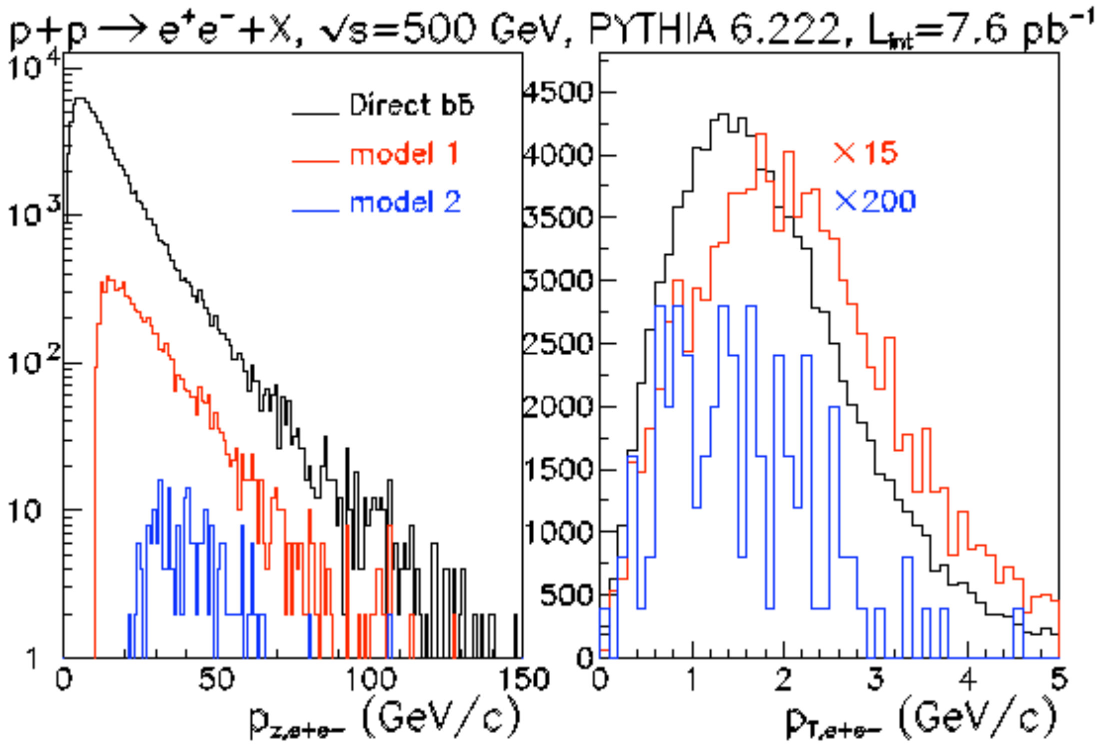
- high energy electrons and positrons (E>10 GeV)
- require detection at very forward angles
- e+(e-) from γ^* little affected by “modest” isolation (20mr half-angle cone)
- best solution for charge sign would be a dipole magnet (difficult for any collider)

Azimuthal angle for $\gamma^* \to e+e-$



- e+ and e- in separate modules except when γ^* has large p_T
- Azimuthal angle required for analyzing power measurement
- Resolution is primarily from measuring energies of e+ and e-
- Model 2 covers full azimuth despite modular coverage

Dileptons from open beauty at large x_F

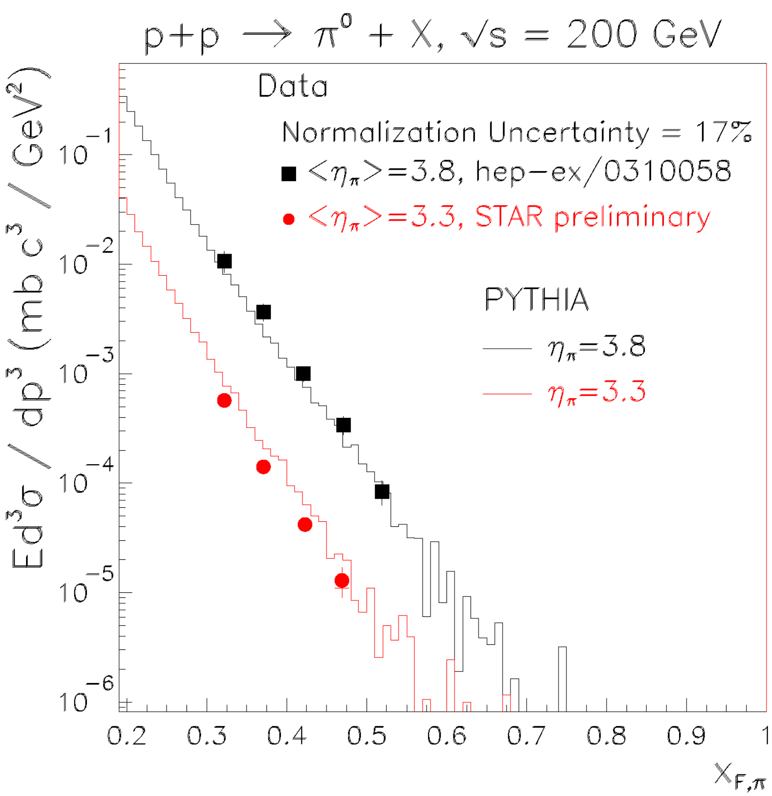


Comments…

- open beauty dileptons are a background 2x larger than DY for PHENIX $\mu^+\mu^-$
- direct production of open beauty results in ~15% background at large xF
- large forward acceptance for the future would require discrimination (isolation)

Backgrounds

- h±/e± discrimination – requires estimates of p+p collisions and EMcal response
- charged/neutral discrimination
- photon conversion background – requires estimates of p+p collisions and materials

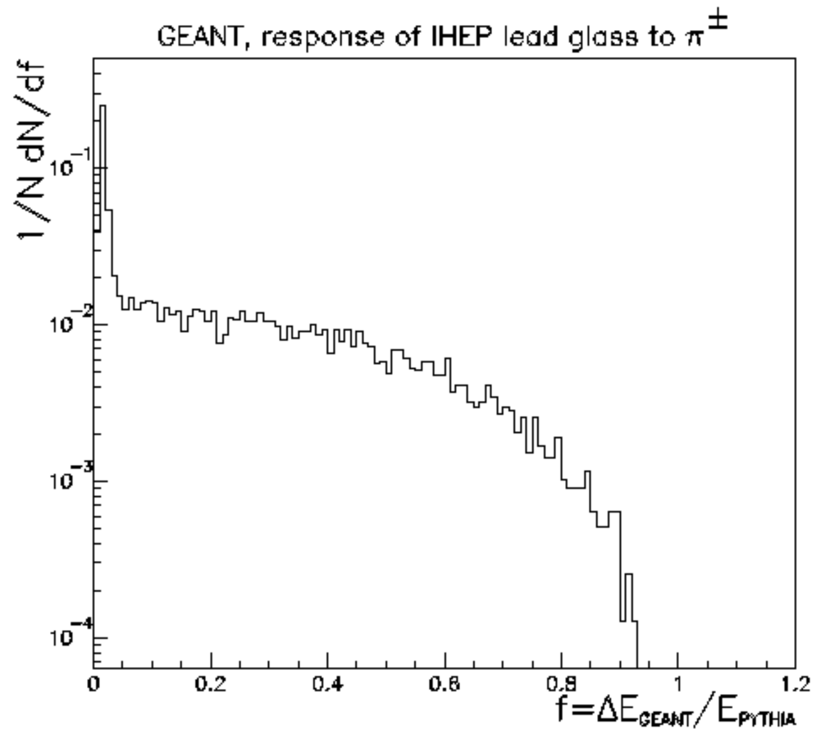


hep-ex/0403012

- PYTHIA 5.7 compared well to √s=200 GeV data [PRL 97 (2006) 152302]
- Little change until "underlying event" tunings for LHC created forward havoc

⇒ Stick to PYTHIA 6.222 for estimates

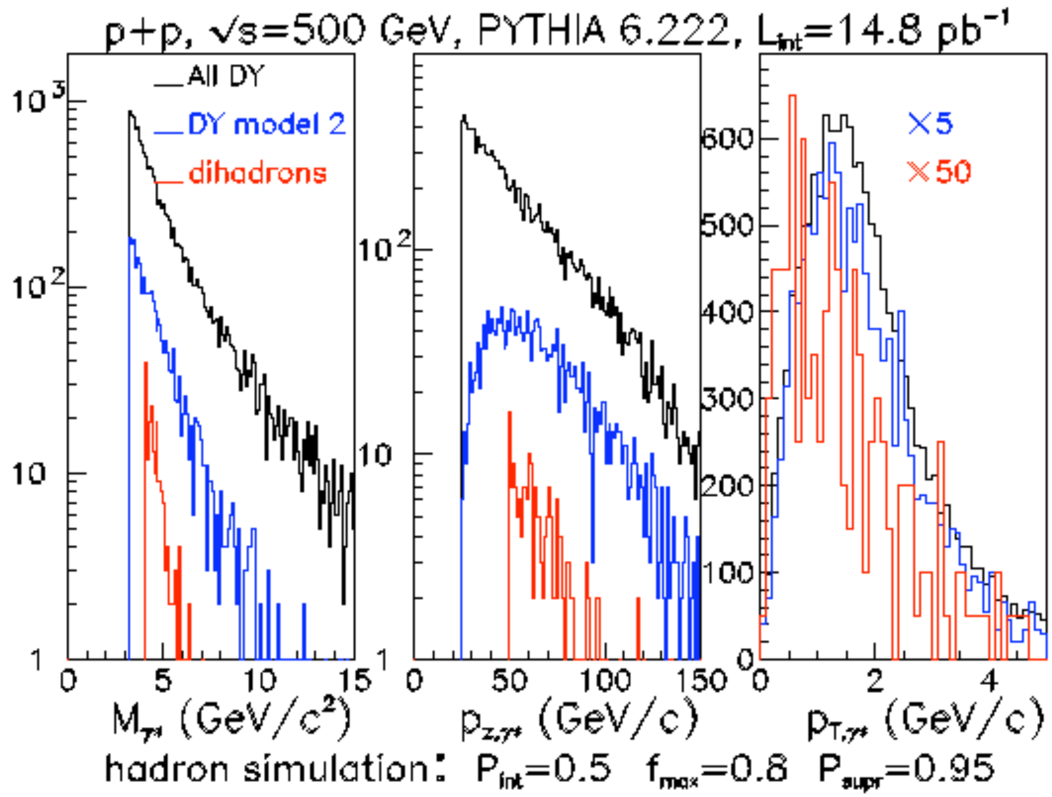
Strategy for estimates



GEANT simulation of EMcal response to E>15 GeV $\pi^{\pm}$ from PYTHIA 6.222 incident on $(3.8\text{cm})^2$x45cm lead glass calorimeter

- ~10^{12} p+p interactions in 50 / pb at $\sqrt{s}$=500 GeV $\Rightarrow$ full PYTHIA/GEANT not practical
- Parameterize GEANT response of EMcal and use parameterized response in fast simulator applied to full PYTHIA events
- Estimate rejection factors from GEANT for hadron calorimeter and preshower detector (both critical to $h^{\pm}/e^{\pm}$ discrimination)
- Explicit treatment in fast simulator to estimate pathlengths through key elements (beam pipe and preshower), to simulate photon conversion to e+e- pair
- Estimate effects from cluster merging in EMcal ($d < \varepsilon d_{cell}$ / recommended is $\varepsilon \approx 1$)
- Estimate/simulate EMcal cluster energy and position resolutions. σ_E=15%/$\sqrt{E}$ and $\sigma_{x(y)}$=0.1d_{cell}, used to date for $\pi^0 \rightarrow \gamma\gamma$ rejection.

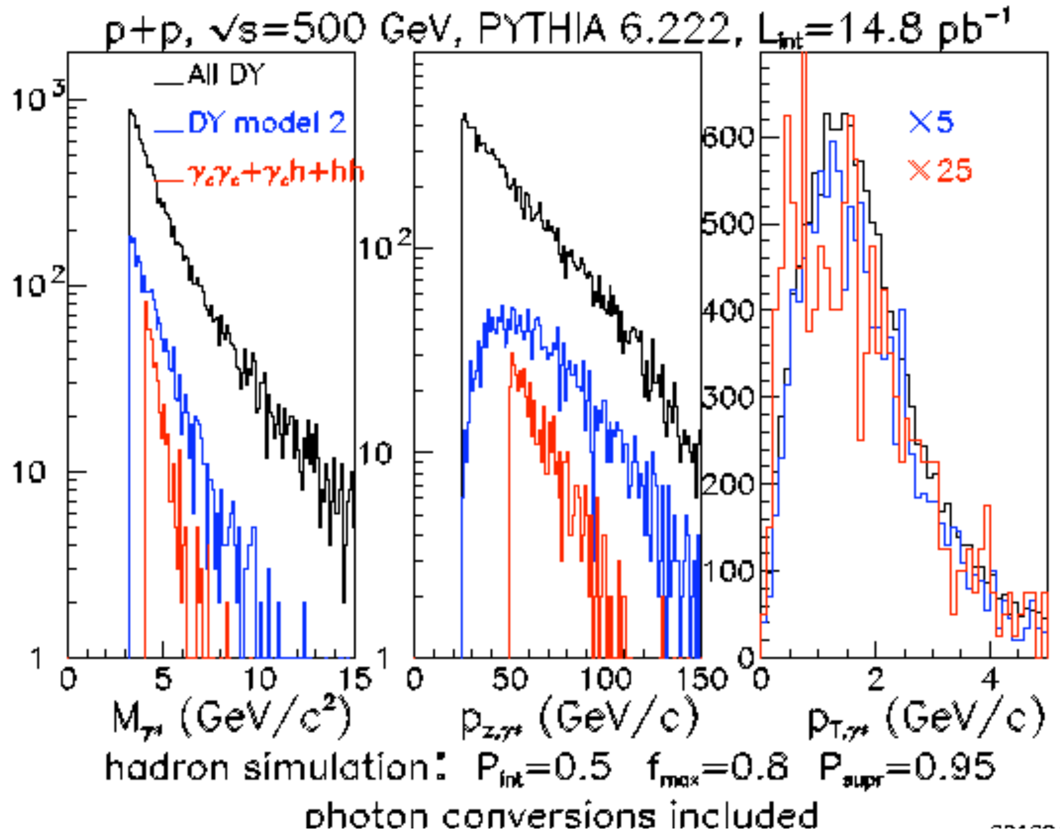
Di-hadron background estimate 1



Comments…

- No cluster simulation included
- Suppression probability consistent with full GEANT treatment for E=10 GeV π
- dN/df modeled by uniform distribution to f_{max} is too simplistic

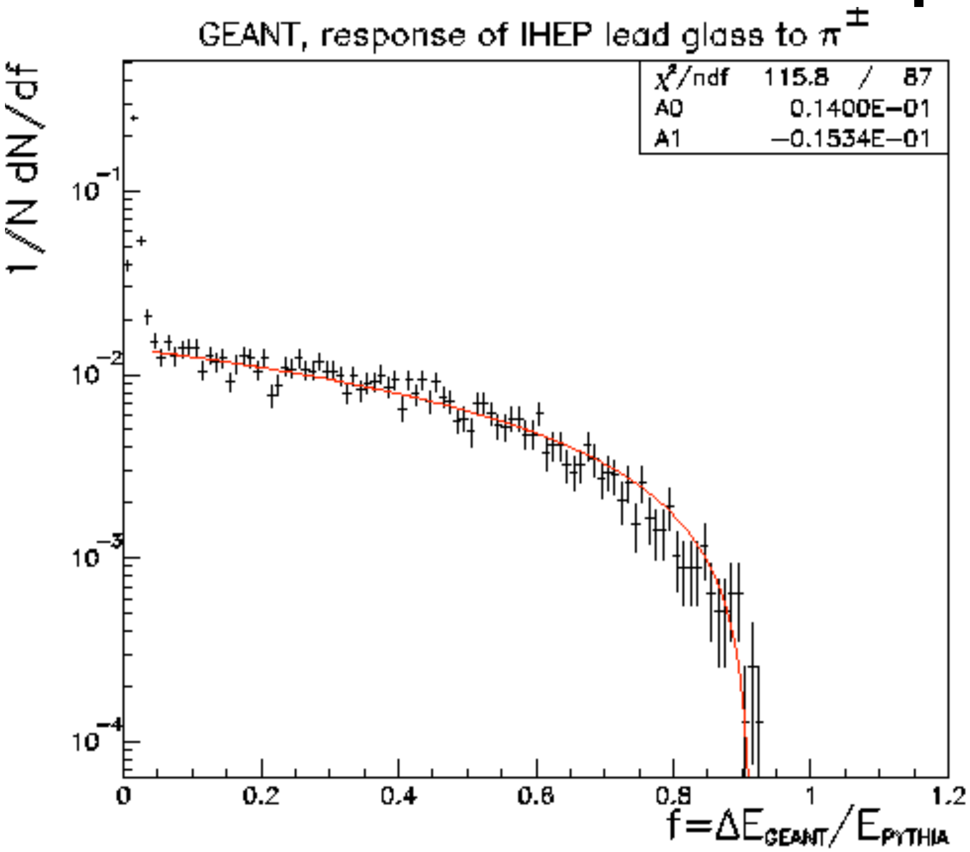
Estimate 2 – first look at γ



Comments:

- ISR low-mass e+e- DY reports limiting background as conversion photons (PLB91,475)
- $N(\gamma_c\text{-}\gamma_c)=0.25N_{back}$ $N(\gamma_c\text{-}h^{\pm})=0.47N_{back}$ $N(h^{\pm}\text{-}h^{\pm})=0.28N_{back}$
- Require $\pi^0\rightarrow\gamma\gamma$ suppression
- dN/df modeled by uniform distribution to f_{max} too simplistic

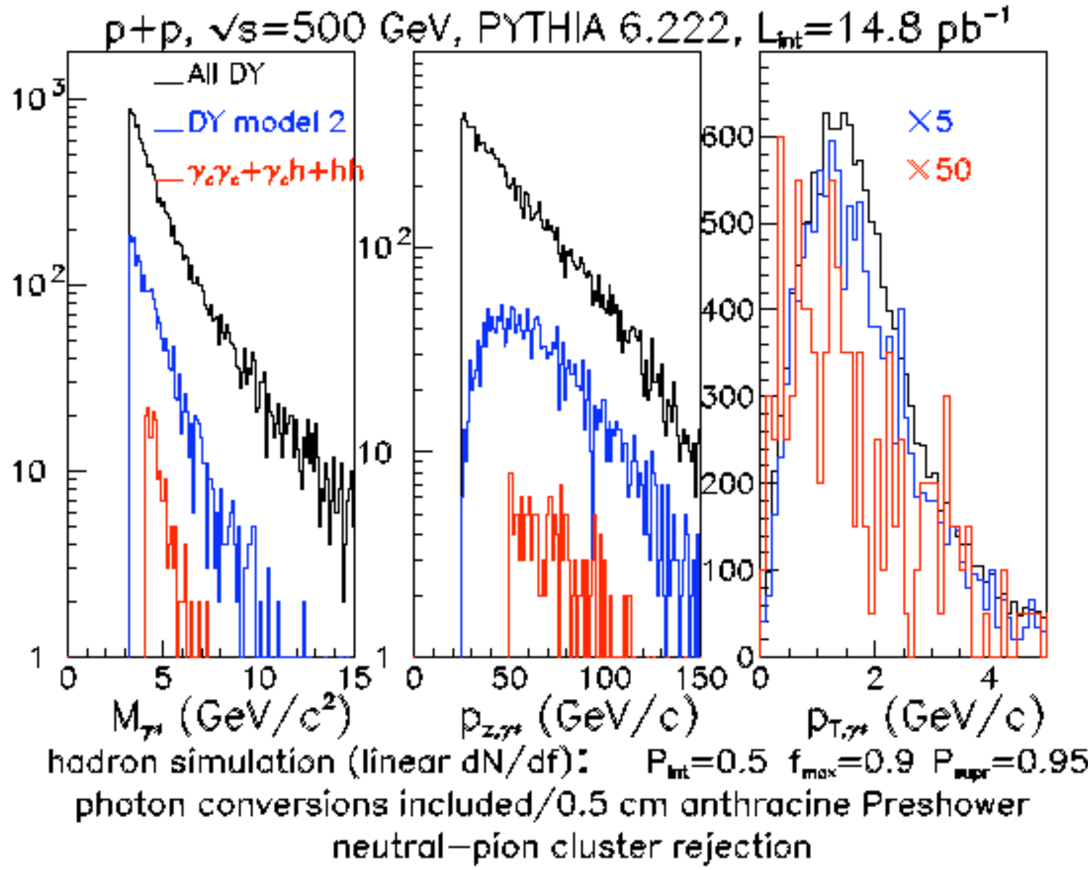
Revisit EMcal response to hadrons



GEANT simulation of EMcal response to E>15 GeV $\pi^{\pm}$ from PYTHIA 6.222 incident on $(3.8cm)^2$x45cm lead glass calorimeter

- Uniform dN/df too simplistic
- GEANT response not so different from 57-GeV pion test beam data from CDF [hep-ex/060808 and presentation file]
- Linear fit to dN/df gives χ^2/DOF=1.3
- Increased sophistication in fast simulator for hadronic response of EMcal still neede

Estimate 3



Comments:

- Conversion photons significantly reduced by $\pi^0 \rightarrow \gamma\gamma$ veto
- Preshower thickness tuned, although perhaps is not so critical given photon veto
- Linearly decreasing dN/df estimates smaller hadronic background ⇒ increased sophistication needed for reliable estimates, although other model uncertainties could easily dominate.

Staging

Assumptions:

1) ~4 week polarized proton test run at $\sqrt{s}$=500 GeV in RHIC run 11

2) 12 week polarized proton W production run at $\sqrt{s}$=500 GeV in RHIC run 12

3) 12 week polarized proton W production run at $\sqrt{s}$=500 GeV in RHIC run 13

Planned Staging:

1) Hcal + newly constructed BBC at IP2 for RHIC run 11 with goals of establishing impact of 3IR operation and demonstrate calibration of Hcal to get first data constraints on charged hadron backgrounds

2) Hcal + EMcal + neutral/charged veto + BBC for RHIC run 12 with goals of zero-field data sample with L_{int}>50 / pb and P_{beam}=50% to observe dileptons from J/ψ, Υ and intervening continuum. Split-dipole tests envisioned.

3) Hcal + EMcal + neutral/charged veto + BBC + split-dipole for RHIC run 13 with goals data sample with Lint>50 / pb and Pbeam=50% to observe dileptons from J/ψ, Υ and intervening continuum to address whether charge sign discrimination is required

Conclusions

- Acceptance with existing modular apparatus looks adequate for feasibility experiment
- First estimates show that DY can dominate over hadronic, conversion photon and open beauty backgrounds

⇒ Proceed with development of Letter of Intent for DY feasibility test aimed at running in parallel with W measurement, pending demonstration that impact of third IR is acceptable

- **The future of CGC studies at RHIC is large x_F Drell-Yan production**